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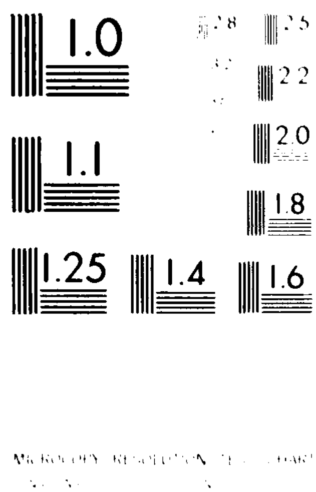
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FINAL REPORT ON THE INVESTIGATION INTO HYDRAULIC GEAR PUMP EFFICIENCIES IN THE FIRST FEW HOURS OF THE PUMP'S LIVES AND A COMPARATIVE STUDY OF ACCELERATED LIFE TESTS METHODS ON HYDRAULIC FLUID POWER GEAR PUMPS

(PART III OF III PARTS)

BY: The Fluid Power Institute
Milwaukee School of Engineering

Under Contract #DAAK70-77-C-0214
to the U.S. Army Mobility Equipment
Research and Development Command
Fort Belvoir, Virginia

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the overall efficiency tests, durability and endurance tests at various oil contamination levels of the eighteen gear pumps previously tested in report parts I and II of this contract.

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(PART III OF III PARTS)

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TABLE OF CONTENTS

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LIST OF FIGURES

3.0 DURABILITY, ENDURANCE, AND PERFORMANCE TESTS

3.1 Introduction

This report is a continuation of Parts I and II of MSOE-MERADCOM report entitled "An Interim Report on the Investigation into Gear Pump Efficiencies During the First Few Hours of the Pumps' Lives and a Comparative Study of Accelerated Life Test Methods on Hydraulic Fluid Power Gear Pumps", dated November 12, 1979 Contract #DAAK70-77-C-0214.

The twelve pumps broken-in on clean oil Part I were subjected to two types of life tests at various fluid contamination levels to determine their durability and endurance characteristics. The instrumentation calibration procedures and test facilities developed in Parts I and II were utilized in this effort. Before the life tests were conducted, a power conversion test was conducted on each pump at various pressures and speeds and at two different inlet oil temperatures in accordance with NFPA T3.9.17R1 Draft No. 5.

3.2 Program Objectives

To investigate the feasibility of accelerated life tests on hydraulic fluid power gear pumps by comparing the high cycle rate durability test and the MIL P52675 1000 hour endurance test at various elevated contamination levels.

3.3 Test Requirements

3.3.1 Power Conversion Tests at 120 and 180°F prior to life tests in accordance with NFPA T3.9.17R1 Draft 5.

3.3.2 High Cycle Rate Durability Test at three different oil contamination levels. MERADCOM Test Procedure Method for Establishing the Durability of a Fixed Displacement Fluid Power Pump 28 February 1978. See Appendix E.

3.3.3 Low Cycle rate 1000 hour endurance test at one contamination level in accordance with MIL-P-52675 "A(ME)" 22 August, 1973 paragraph 4.5.2.2.4.

3.3.4 Pressure wave shape on life tests to conform to SAE J343C Hose Test Procedure. Photographs of wave shapes are in Appendix A of this report.

3.3.5 Other test standards used in this effort are referenced in report parts I and II.

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Figure No. 3.3.6

Number of Pump Test Specimens Broken-in With Clean Oil to be Durability and Endurance Tested Arranged by Manufacturer, Type of Life Test and Oil Contamination Level

Type of Test and Oil Contamination Level	Number of Test Specimens and Manufacturer		
	M1	M2	M3
Durability clean oil less than 200 particles/ml greater than 10 um	1	1	1
Durability dirty oil 800-1000 particles/ml greater than 10 um	1	1	1
Durability dirty oil 1500-2000 particles/ml greater than 10 um	1	1	1
Encurance MIL P52675 dirty oil 800-1000 particles/ml greater than 10 um	1	1	1

3.4 Brief Test Procedure

Twelve gear pumps, four identical models from each of the three contributing manufacturers were tested in four lots of 3 each. All manufacturers contributed pumps which were similar in key parameters. The three pumps in each lot were all tested simultaneously on the same test rig and connected to a common reservoir. The tests consisted of cyclic endurance running at three different contamination levels and two different cycle rates in accordance with figure no. 3.3.6. The pressure cycle rate for the durability test was 1 cycle/second and for the 1000 hour endurance test it was 1 cycle/ 10 seconds.

For purposes of these tests, all pumps were assumed to have identical ratings of 2500 psi 2700 rpm and approximately $3in^3$/rev displacement. It should be noted that with the above assumption, two manufacturers' pumps were tested at their rated pressure while one was tested at 120% of its rated pressure. Similarly all three manufacturers' pumps were tested below their rated speeds.

Throughout the duration of the test, the parameters listed in figure 3.4.1 were monitored at the intervals shown there.

The detailed test procedure and circuit schematics are in Appendix A of this report.

Prior to the durability and endurance tests, a power conversion test was conducted at 120° and 180°F on the twelve pumps that were broken in with clean oil. Power conversion tests were also run on the 6 pumps broken-in with dirty oil. On one test specimen from M2, subsequent computer processing of the power conversion data revealed that the data was seriously in error and the test could not be re-run. Consequently; there are valid power conversion results from only 17 of the eighteen test specimens.

Figure 3.4.1

Parameter Monitoring Intervals
for Pump Life Tests

Parameter	Monitoring Interval
Inlet Temp. °F	0.5 Hrs.
Outlet Temp. °F	0.5 Hrs.
Inlet Pressure PSI	0.5 Hrs.
Outlet Pressure PSI	0.5 Hrs.
Input Speed RPM	0:5 Hrs.
Output Flow GPM	0.5 Hrs.
Contamination Level Particles/Ml	24 Hrs. or less as required to maintain the directed level

Figure 3.5.1

MAXIMUM OVERALL EFFICIENCY SUMMARY FROM POWER CONVERSION TESTS

All power conversion test data on 17 specimens was scanned for the maximum overall efficiency. The minimum efficiency column represents that test specimen whose peak efficiency was lowest of all that manufacturer's specimens. All values are given in percent.

Pump Manufacturer	120°F Inlet Temperature				180°F Inlet Temperature			
	Max Eff	Min Eff	Ave Eff	Std Dev	Max Eff	Min Eff	Ave Eff	Std Dev
M1 6 Test Specimens	88.2	84.1	85.9	1.34	84.1	81.3	82.9	1.03
M2 5 Test Specimens	94.6	84.1	89.1	4.07	93.4	81.8	86.6	5.07
M3 6 Test Specimens	94.5	86.6	88.4	2.76	88.3	80.8	84.3	2.44

Average overall efficiency for 17 test specimens at 120°F is 87.8%.

Standard deviation in overall efficiency for 17 test specimens at 120°F is 2.94.

Average overall efficiency for 17 test specimens at 180°F is 84.6%.

Standard deviation in overall efficiency for 17 test specimens at 180°F is 3.3.

Figure 3.5.2

NORMALIZED DISPLACEMENT RATIO SUMMARY

Method 1 for calculating the displacement ratio is from NFPA T3.9.17R1. It involves scanning all data for the maximum flow to speed ratio and approximating that as the 100% volumetric efficiency point. Method 2 involves the extrapolation of the pressure-flow curves back to zero pressure axis and using the flow at that zero intercept as the 100% volumetric efficiency point. The displacement ratio is calculated by taking the values from methods 1 and 2 and dividing them by the manufacturer's published displacement.

Pump Manufacturer	120°F Inlet Temperature								180°F Inlet Temperature							
	Method 1				Method 2				Method 1				Method 2			
	Max	Min	Ave	Std Dev	Max	Min	Ave	Std Dev	Max	Min	Ave	Std Dev	Max	Min	Ave	Std Dev
M1 6 Test Specimens	.985	.969	.978	.006	1	.948	.972	.017	1	1.01	.961	.986	1	.948	.961	.018
M2 5 Test Specimens	1	.996	.998	.002	1	.996	.998	.002	.993	.972	.982	.007	1	.986	.997	.006
M3 6 Test Specimens	.990	.971	.982	.007	1	.982	.988	.009	.976	.954	.965	.009	1	.951	.972	.02

Average displacement ratio for 17 test specimens at 120°F is .986 using method 1 and .986 using method 2.

Standard deviation in displacement ratio for 17 test specimens at 120°F is .005 for method 1 and .011 for method 2.

Average displacement ratio for 17 test specimens at 180°F is .978 using method 1 and .977 using method 2.

Standard deviation in displacement ratio for 17 test specimens at 180°F is .03 using method 1 and .03 using method 2.

Figure 3.6.1

Tabulated Durability and Endurance Test Results

Test Type	Pump Mfg.	Pump Code #	Beginning Flow Rate GPM	Ending Flow Rate GPM	Percent Change	Completed Cycles/Hrs.	Type of Failure
Durability Clean Oil < 200 particles per ml > 10 um	M1	57740	30	29.2	-2.7	500,000 / 167	Test completed No failure
	M2	56941	28.3	29.7	+4.9	500,000 / 167	Test completed No failure
	M3	17453	30.5	30.3	-.66	500,000 / 167	Test completed No failure
Durability Dirty Oil 800-1000 particles/ml > 10 um	M1	12566	30.2	22.8	-24.5	500,000 / 165	Test completed No failure
	M2	16439	29.4	29.0	-1.4	227,273 / 75	Bearing failure due to excessive wear
	M3	10281	34.2	22.0	-35.7	500,000 / 165	Test completed No failure
Durability Dirty Oil 1500-2000 particles/ml > 10 um	M1	25331	30.4	27.2	-10.5	115,000 / 38	Bearing failure due to excessive wear
	M2	05585	30.1	25.0	-17	171,600 / 57	Bearing failure due to excessive wear
	M3	63661	30.4	22.8	-25	155,000 / 52	Bearing failure due to excessive wear
Endurance Dirty Oil 800-1000 particles/ml > 10 um	M1	84378	28.4	20.0	-29.6	46,000 / 136	Bearing failure due to excessive wear
	M2	11458	28.0	28.4	-1.4	47,700 / 142	Bearing failure due to excessive wear
	M3	18102	33.5	13.5	-59.7	165,500 / 464	Test terminated due to 50%+ drop in efficiency.

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3.7 Observations

3.7.1 Using either of the two methods for determining displacement produces a value for the displacement that was about 0.8% lower at 180°F than at 120°F for these tests.

3.7.2 For manufacturer 1, the standard deviation using method #2 was larger than all other manufacturer and methods. This came about because the flow vs. speed characteristics at constant pressure are not parallel. There is presently no explanation.

3.7.3 The statistical spread in overall efficiency of any one of these manufacturers is essentially unaffected by the test temperature.

3.7.4 Raising the temperature from 120°F to 180°F resulted in about a 3 percentage point drop in overall efficiency during these tests.

3.7.5 The earlier break-in studies of eighteen test specimens showed that a gear pump's mechanical efficiency was most likely to change during the first three hours of a gear pump's life whereas the volumetric efficiency was unlikely to change. During the durability tests with clean oil, all three gear pumps experienced a slight improvement in output flow beginning at 5 to 10 hours and lasting for 20 to 50 hours before settling out.

3.8 Conclusions

3.8.1 Based upon the statistical analysis of the 17 test specimens a minimum overall efficiency requirement of 81% at 120°F could be used when ordering commercial gear pumps. The criterion used to arrive at that figure consists of the average of overall efficiency minus two standard deviations. This encompasses more than 95% of the samples being accepted.

3.8.2 There is virtually no difference in the two methods used to calculate the displacement ratio therefore, the assumptions used in NFPA T3.9.17R1 to calculate simple displacement appear to be valid.

3.8.3 Because there is only a 1.4% difference between the manufacturer's published displacement and the experimental displacement as calculated herein. One can conclude that manufacturer's published values are fairly representative of these production run pumps.

3.8.4 Flow, as the sole measure of a pump's integrity, appears to be inadequate. One manufacturer's output flow proved to be impervious to contamination levels below 1000 particles/ml > 10 um but shortly experienced bearing failures without warning. This occurred twice. Perhaps the monitoring of torque as well as flow in the NFPA Comtaminaion Sensitivity tests would provide greater insight into the overall integrity of the test specimen at any given moment in its history.

3.8.5 As output flow falls off with time, it becomes more difficult to control outlet temperature. That is, temperature rises as flow drops. This is caused by the increased fraction of outlet flow that is "re-cycled" into the pump's inlet side which then results in less new and cool oil to reduce the heat build up. Granted, outlet temperature increase does depend upon the temperature control system and the pump's inlet oil temperature, however, the observations here beg for further investigation of thermal instability, especially at lower speeds where slippage becomes a greater fraction of displaced flow.

3.8.6 Durability and Endurance test standards which permit fluid contamination levels to be as high as 1000 particles/ml > 10 um are much too permissive. When the contaminant is abrasive, as was the AC Fine Test Dust used in these experiments, damage occurred to both the hydraulic and mechanical members far too early. A contamination level of 1000 particles/ml > 10 um is actually a form of contamination sensitivity test, not a durability test. At the very least, it is an accelerated life test.

3.8.7 The test procedure used in this program goes a substantial distance in simulating real multi-pump mobile hydraulic systems with moderate to poor filtration. That is, the test system consisted of three pumps driven through a gear box by a common prime mover. Additionally, the reservoir was common to all pumps which allowed a contamination "cross-talk" to take place. Under not-so-rare field conditions of poor to moderate filtration and multiple pumps (there was no filtration present in the elevated contamination tests) one could expect contaminant to be both re-cycled (multipassed) and ingressed at the same time. The test procedure used in this program accomplished these things.

3.8.8 Because of the contamination cross-talk permitted (or perhaps, forced) in a multi-pump test, one pump undergoing wear can adversely affect the other pumps because of the wear debris generated by the first. When the M1 pump failed at 40 hours during a contaminated durability test, it was accompanied by a sudden, uncontrolled increase in contamination level -- from a desired level of 2000 particles/ml > 10 um to about 9000 particles/ml > 10 um. This rise in contamination correlates with a decided flow degradation of one of the other two remaining pumps with the other unmeasurably affected.

3.8.9 Sustained exposure to an elevated but modest level of abrasive contamination will not always result in a gradual flow degradation, however, the contamination may eventually destroy sleeve bearings resulting in a catastrophic pump failure.

3.8.10 Sleeve bearings appear to be more susceptible to failure in the presence of modest contamination levels than are roller bearings.

3.8.11 Some gear pumps will undergo slight flow degradation even when the contamination level is held to fewer than 200 particles/ml > 10 um.

3.8.12 When either the high cycle rate durability or the 1000 HR endurance test is conducted at an elevated, moderate, controlled contamination level it provides a good method of testing the many ways that contamination attacks a pump, including bearings.

3.8.13 The danger in testing more than one pump at the same time and with a common reservoir lies in the inevitability that the earliest failing pump will cross-contaminate the other pump(s) and precipitate their earlier-than-normal demise. Evidence of this cross-contamination was apparent in these tests and in some, but not all instances, the contaminant rise at the time of one pump's failure correlated with flow drops in the surviving pumps. This undoubtedly shortened the survivor's lives, however, it is not concluded that simultaneous testing, per se, shortens pump life.

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3.8.14 Endurance and durability testing at moderately elevated contamination levels can provide insight into a gear pump's susceptibility to bearing failure as well as to its susceptibility to flow degradation.

3.8.15 The use of a pilot operated relief valve as the cyclic loading device in an endurance test appears to be ideal for several reasons:

3.8.15.1 It can be tuned, to a limited extent, to control the rise and fall times.

3.8.15.2 Along with pilot operated check valves, the contaminated life test circuit can be isolated from the clean control circuit.

3.8.15.3 It provides a "gentle" cycle in that there is essentially no pressure overshoot.

3.8.15.4 It eliminates the need to cycle the main power flow with a large solenoid operated valve, thus maximizing life expectancy of the control circuit.

3.9 Recommendations

3.9.1 The present method used in NFPA T3.9.17R1 for determing displacement should be retained.

3.9.2 Refering to conclusion 3.8.1, gear pump specimens which have approximately one-fifth and five times the displacements used in these studies should be tested according to NFPA T3.9.17R1 in order to determine if the 81% minimum overall efficiency criterion is valid for other gear pump sizes.

3.9.3 A round-robin test program should be conducted in alliance with industrial laboratories for the purpose of evaluating the validity of NFPA T3.9.17R1.

3.9.4 The substantial volume of performance data collected in these studies should be used as a basis of further studies, namely:

3.9.4.1 Development of a suitable mathematical model of the gear pumps which were tested.

3.9.4.2 Investigation of alternate methods of determining displacement.

3.9.4.3 Determination of the root causes of the spread in overall efficiencies, ie, volumetric efficiency vs. mechanical efficiency.

3.9.4.4 Investigate possible causes for the displacement difference between the manufacturers' and the experimental values.

3.9.4.5 Investigate the effects that temperature increase has upon the relative values of volumetric and mechanical efficiencies.

3.9.5 Conduct further tests with several constant temperatures, and several viscosities (different fluids).

3.9.6 Future controlled contamination endurance and/or durability tests should be conducted with some filtration deployed at all times and contamination level monitoring should be done at intervals more frequent than once each day. On-line, continuous monitoring would be best, accompanied by automatic filtration and injection correction.

3.9.7 Contamination sensitivity testing of gear pumps should require the measurement of input torque as well as output flow.

3.9.8 Future contaminated oil tests should require the monitoring of air borne and liquid borne noise levels, spectrum analysis of pressure ripple, vibrations and accoustic emmissions, to see if there is any correlation between these parameters and an impending pump failure.

3.9.9 A thermal stability test should be developed for gear pumps.

3.9.10 Test standards should carry requirements that contamination levels be maintained at fewer than 200 particles/ml > 10 um except for accelerated life testing.

3.9.11 Since the waveform contained in the SAE J343C hose test standard does not take into account the inevitable pressure ripple that accompanies pump output, it should be abandoned per se and replaced with a specification which deals with the mid-point maximum and mid-point minimum.

3.9.12 Because a gear pump's volumetric efficiency may migrate (up or down) as much as 3% during the first 50 hours or so of its life, MIL-P-52675 should allow at least a 10% change in overall efficiency from the beginning to the end of the 1000 HR endurance test.

3.9.13 Using the particle count data collected during the endurance and durability tests, carry out an analysis to determine the liklihood that the finer particles were building up as the test progressed.

3.9.14 Using results of the durability and endurance tests, investigate the degree of correlation with standard contamination sensitivity test results.

3.9.15 Analyze all FPI field oil samples to determine average contamination levels in various types of mobile and industrial equipment.

APPENDIX A

DETAILED TEST PROCEDURE

APPENDIX A: TEST PROCEDURE

System Description

A eighty gallon cylindrical shaped reservoir with a conical bottom was used to insure that no contaminant would settle to the bottom. A diffuser was installed in the center of the reservoir just below the oil level which created a mixing action inside the reservoir to keep the contaminants in uniform suspension. A fluid conditioning circuit was included with the main reservoir for cooling and control of the contamination level.

A three element three micrometre nominal filter was used for filtering the fluid with a bypass valve so the fluid could be either routed through the filter or around it. When the fluid bypassed the filter, it went through two sixty micrometre stainers to remove the large particles. The sample tap was installed in an elbow in the return line before the filters and strainers.

System Qualification

Before the twelve gear pumps were tested, both the hydraulic circuit and the instrumentation system were qualified.

For the clean oil test the fluid conditioning circuit and the three test pumps were run for several hours at minimum pressure with the filter in the circuit. Oil samples were taken at selected intervals to monitor the stability of the contamination level. For the three contaminated oil tests the system was contaminated with AC Fine Test Dust to the level specified, with only the strainers in to remove larger particles. The three test pumps were run for several hours at minimum pressure with the filter out of the circuit. Oil samples were taken at selected intervals to monitor the stability of the contamination level.

This procedure was conducted to determine if the contamination level would increase, decrease, or remain the same when the system was running with no filters in. The ideal condition would be for the contamination level to remain the same meaning that the test circuit does not add contaminant nor did it act as a filter or trap, causing the level to decrease. It was found that this system had an adequately stable contamination level while running without a filter.

Initial System Seeding

To contaminate the system oil the following proceuure was used:

1. System was thoroughly cleaned with 3 u filter while running at minimum pressure.
2. A 250 ml oil sample was taken from the system at the sample tap to verify initial clean-up.
3. A quantity of AC Fine Test Dust (0.5 g to 1.0 g, depending upon change needed) was weighed on a triple beam balance and placed into the 250 ml sample bottle.
4. The sample was then agitated with the oil sample shaker for approximately eight minutes to disburse the AC Fine Test Dust.

5. The sample was then added to the system through the top port on the reservoir.

The system was allowed to run at minimum pressure and an oil sample was taken after approximately 30 minutes to determine the contamination level. This process was repeated until the contamination level was within the test specification.

On Line Contamination Regulation Procedure

The contamination level was monitored at least once a day for the remainder of the test. If the contamination level was too high the filters were put back in temporarily. After the filters were removed, another oil sample was taken. This procedure was repeated until the contamination level was within test specifications. In the event that the oil was too clean more AC Fine Test Dust was added by the method previously described. The test system was permitted to continue cycling during the contamination adjusting period which required from 45 minutes to 1 hour to complete. Generally it was found that contaminant had to be added on a regular basis except when a pump failed.

In the event of a pump failure an oil sample was taken and then the system was cleaned up to below 200 particles/ml greater than 10 microns to remove pump wear debris. Before restarting the test, the oil was re-seeded with ACFTD by the method described earlier.

Instrumenation Measurement and Control Systems

The instrumentation and measurement system described in report parts I and II were used for this effort. A block diagram of the measurement system is shown in figure A.1. Orifice plate flowmeters were used in this effort rather than the positive displacement type which were used in parts I and II because of the contaminated oil. Appendix B contains the orifice flowmeter information.

Two timing circuits were used to control the test. One circuit was used to cycle the pressure at the required rate. The other one was used to trigger the data acquisition system in the following manner. Every half hour the pressure would stop cycling for one minute at the high pressure state. After a ten second delay, the data acquisition system would record all test parameters on the teletype. At the end of one minute, the pressure would start cycling again.

All data channels on the data acquisition system except for pump speed were connected to internal alarms for high and low limits. Each channel's alarm could be set individually. At the time data points were recorded, if any test parameter was out of specification, the data acquisition system would automatically shut the test stand down. Failsafes were also included for low oil level in the reservoir and for low pilot pressure to shut the test stand down.

Pressure Control Circuit

A separate pilot supply and pilot operated check valve were used to cycle the outlet pressure. The pilot vent ports on each of the pumps' relief valves were plumbed to the pilot operated check valve. A solenoid operated four-way valve was used to apply pressure to the pilot operated check valve in turn causing it to open or close. When the pilot operated check valve was open the vent ports on the pumps' relief valve were at minimum pressure and so was the pumps' outlet pressure. When the pilot operated check valve was closed the vent ports were blocked so that the pump outlet pressure was at relief valve setting. The circuit is depicted schematically in figure A.2.

The outlet pressure waveshape was in conformance with SAE J343C Hose Test Procedure. The waveshape for each pump was adjusted by using a variable orifice installed between the pressure port and vent port of each relief valve. At the start of each test, the pressure waveshape was monitored on an oscilloscope and the variable orifice was adjusted until the required waveshape was achieved. See figures A.3 through A.14 for actual photographs of pressure waveshapes.

The SAE waveform does not consider pressure ripple which is generated by the pump, therefore on some pumps depending on the ripple, the pressure variance is greater than the required 5%. However, the pumps waveshape met the SAE specifications for rise and fall rates and on and off times.

BLOCK DIAGRAM OF MEASUREMENT SYSTEM

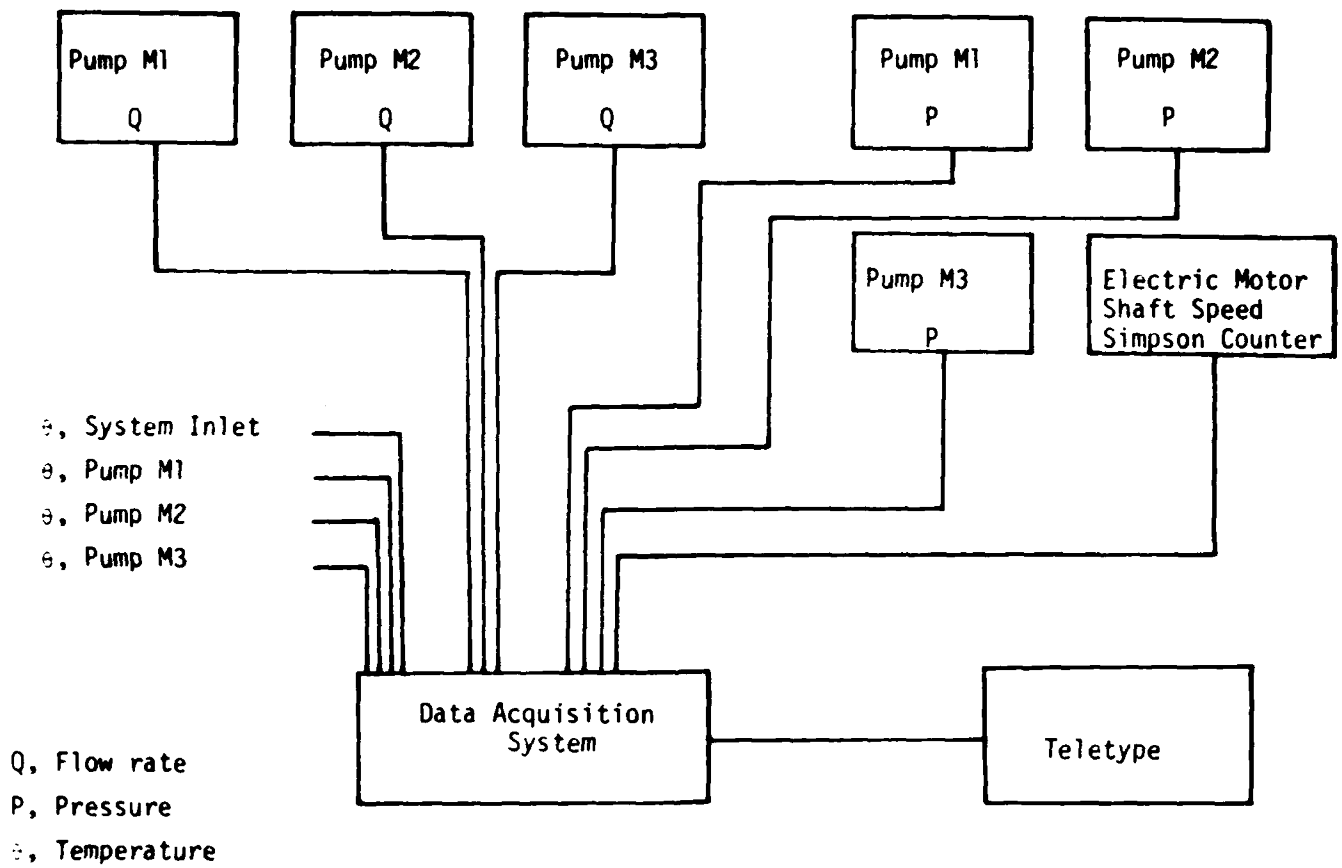
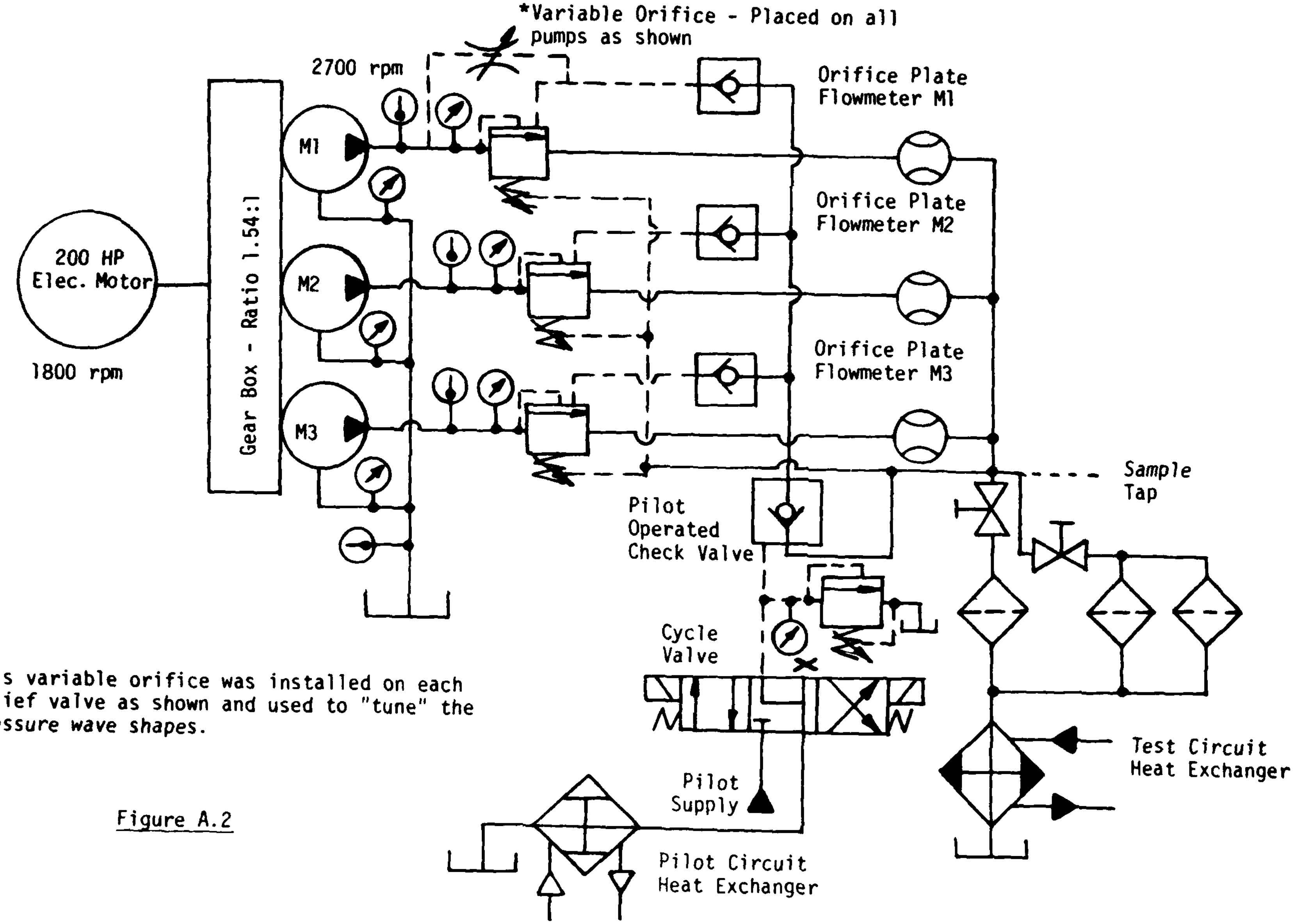


Figure A.1

HYDRAULIC CIRCUIT SCHEMATIC



* This variable orifice was installed on each relief valve as shown and used to "tune" the pressure wave shapes.

Figure A.2

OSCILLOSCOPE TRACES OF OUTLET PRESSURE

Durability Test Clean Oil

Less than 200 particles/ml greater than 10 micrometres

Vertical Axis 1000 psi/cm
Horizontal Axis 0.5 sec/cm

Figure A.3

Mfgr. No. 1
Pump Code No. 47740

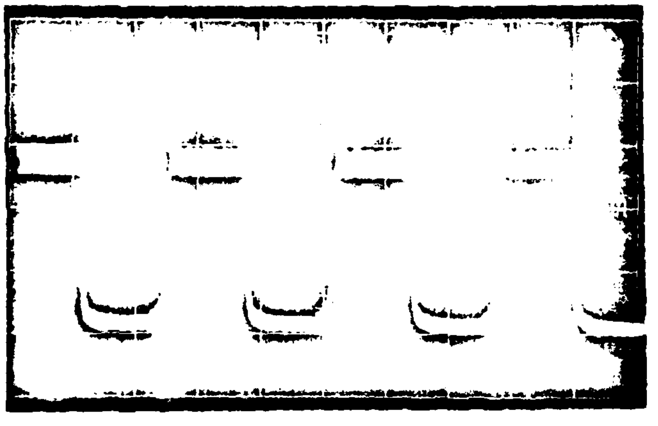


Figure A.4

Mfgr. No. 2
Pump Code No. 56941

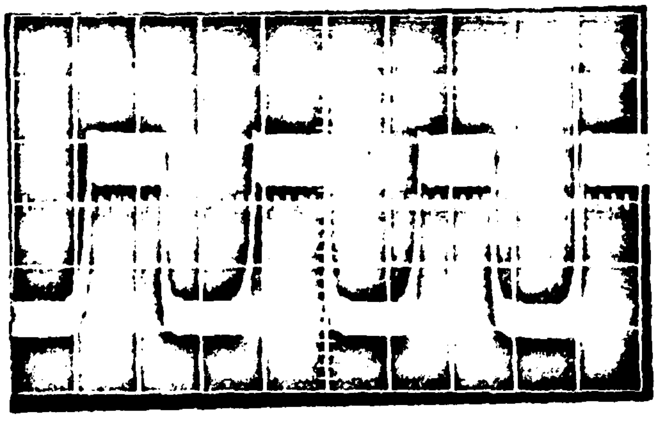


Figure A.5

Mfgr. No. 3
Pump Code No. 17453

OSCILLOSCOPE TRACES OF OUTLET PRESSURE

Durability Test Dirty Oil

800-1000 particles/ml greater than 10 micrometres

Vertical Axis 1000 psi/cm
Horizontal Axis 0.5 sec/cm

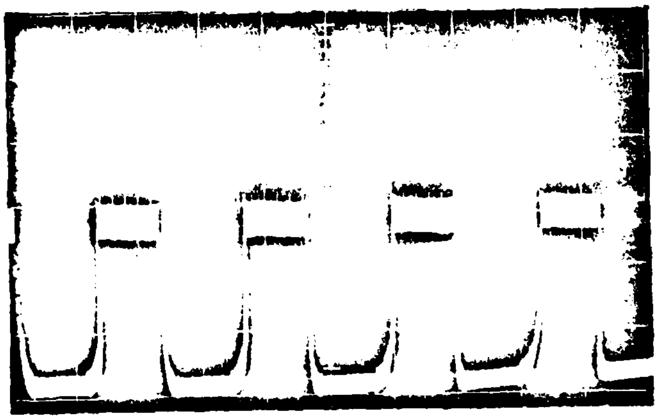


Figure A.6

Mfgr. No. 1
Pump Code No. 12566

Figure A.7

Mfgr. No. 2
Pump Code No. 16439

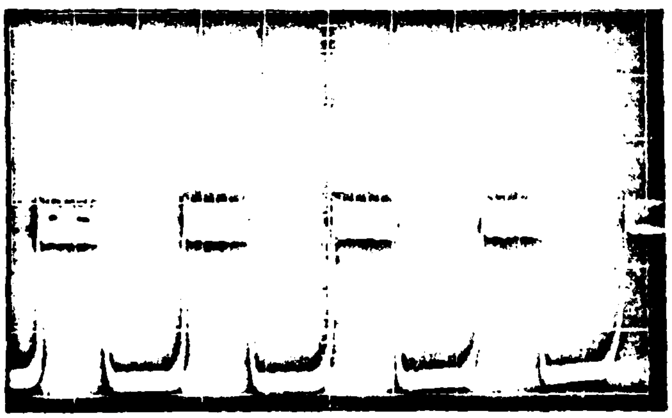


Figure A.8

Mfgr. No. 3
Pump Code No. 10281

OSCILLOSCOPE TRACES OF OUTLET PRESSURE

Durability Test Dirty Oil

1500-2000 particles/ml greater than 10 micrometres

Vertical Axis 1000 psi/cm
Horizontal Axis 0.5 sec/cm

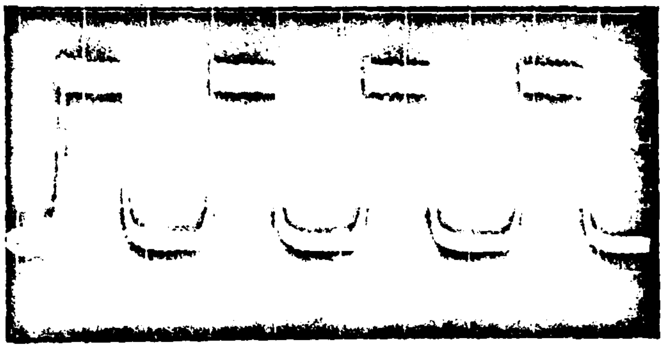


Figure A.9

Mfgr. No. 1
Pump Code No. 25331

Figure A.10

Mfgr. No. 2
Pump Code No. 05585

Figure A.11

Mfgr. No. 3
Pump Code No. 63661

OSCILLOSCOPE TRACES OF OUTLET PRESSURE

1000 Hour Endurance Test Dirty Oil

800-1000 particles/ml greater than 10 micrometres

Vertical Axis 1000 psi/cm
Horizontal Axis 0.5 sec/cm

Figure A.12

Mfgr. No. 1
Pump Code No. 84378

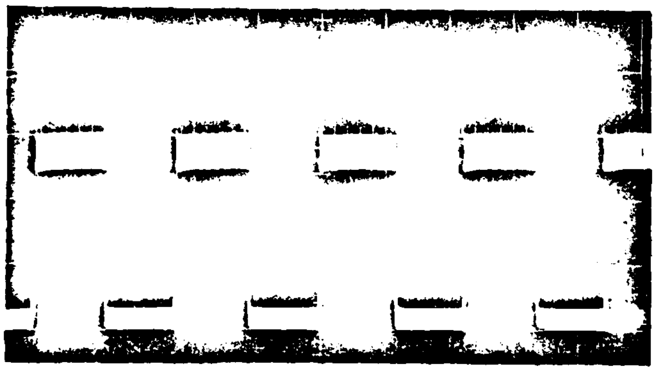


Figure A.13

Mfgr. No. 2
Pump Code No. 11458

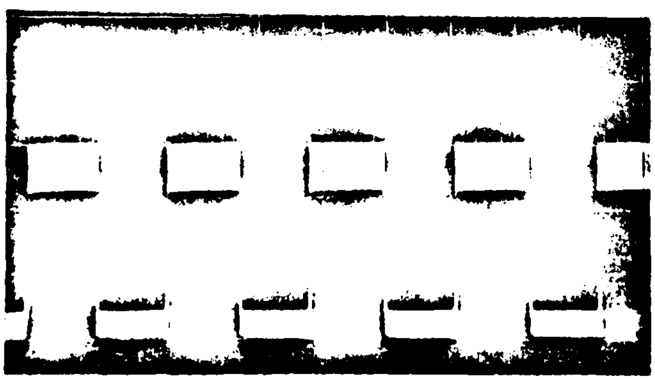


Figure A.14

Mfgr. No. 3
Pump Code No. 18103

APPENDIX B

ORIFICE FLOWMETER CALIBRATION

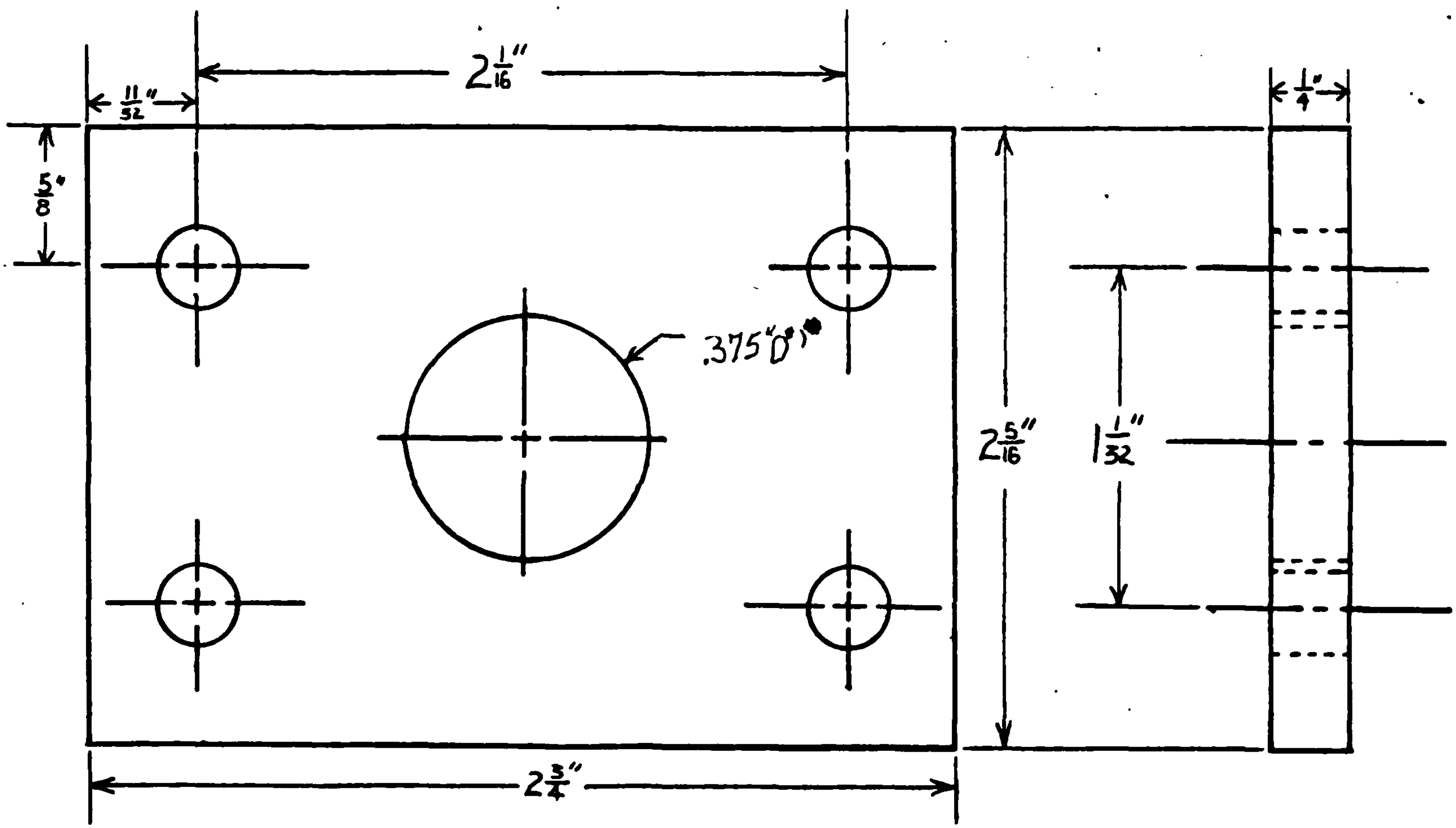
ORIFICE FLOWMETER CALIBRATION

Three orifice plate flowmeters were designed, constructed and calibrated for the contaminated oil life tests because of possible irreversible damage which might occur to a positive displacement flowmeter under these test conditions.

The orifice consisted of a low carbon steel plate with a precision hole machined in the center. See figure B.1. The hole was sized for a 50 psi pressure drop at 50 gpm. To complete the flowmeter, the orifice plate was installed between two 1" 3000 psi SAE 4 bolt flanges with 2 ft. of schedule 80 1" diameter pipe on either side. Pressure taps were installed in each SAE flange so that the pressure drop across the orifice plate could be recorded. Pressure transducers were installed in the pressure taps which produced a DC voltage proportional to the flowrate.

Army ORIFICE PLATE
(NOT TO SCALE)

Figure B.1



* LOCATED IN CENTER OF BOLT PATTERN

FPI PROJECT NO. 50336 7-28-78 RD

The orifice plate flowmeters were calibrated against the positive displacement flowmeter which was calibrated in report part II Program Support. All four flowmeters were connected in series to the test stand as shown in Figure B.2. The data acquisition system was connected to the output of the pressure transducers as shown in figure B.3.

The flowrate was increased at selected intervals, at each data point the voltage output of each transducer and the system temperature were recorded. The flowmeters were calibrated at the start of testing and at the end of the test program. The flowmeters were also calibrated at two different temperatures.

The results revealed that there was no change in calibration from the start to the end of the test program and also that there was no change in calibration for the two different test temperatures.

It was determined empirically from orifice calibration data that the following equation best described the orifice voltage-flow relationship for the orifice:

$$V = 4.237 \times 10^{-3} Q^{1.9175}$$

where V is the differential pressure transducer output voltage in volts and Q is the orifice flow in gpm.

There were no significant differences among the three orifices.

HYDRAULIC SCHEMATIC - ORIFICE PLATE FLOWMETER CALIBRATION

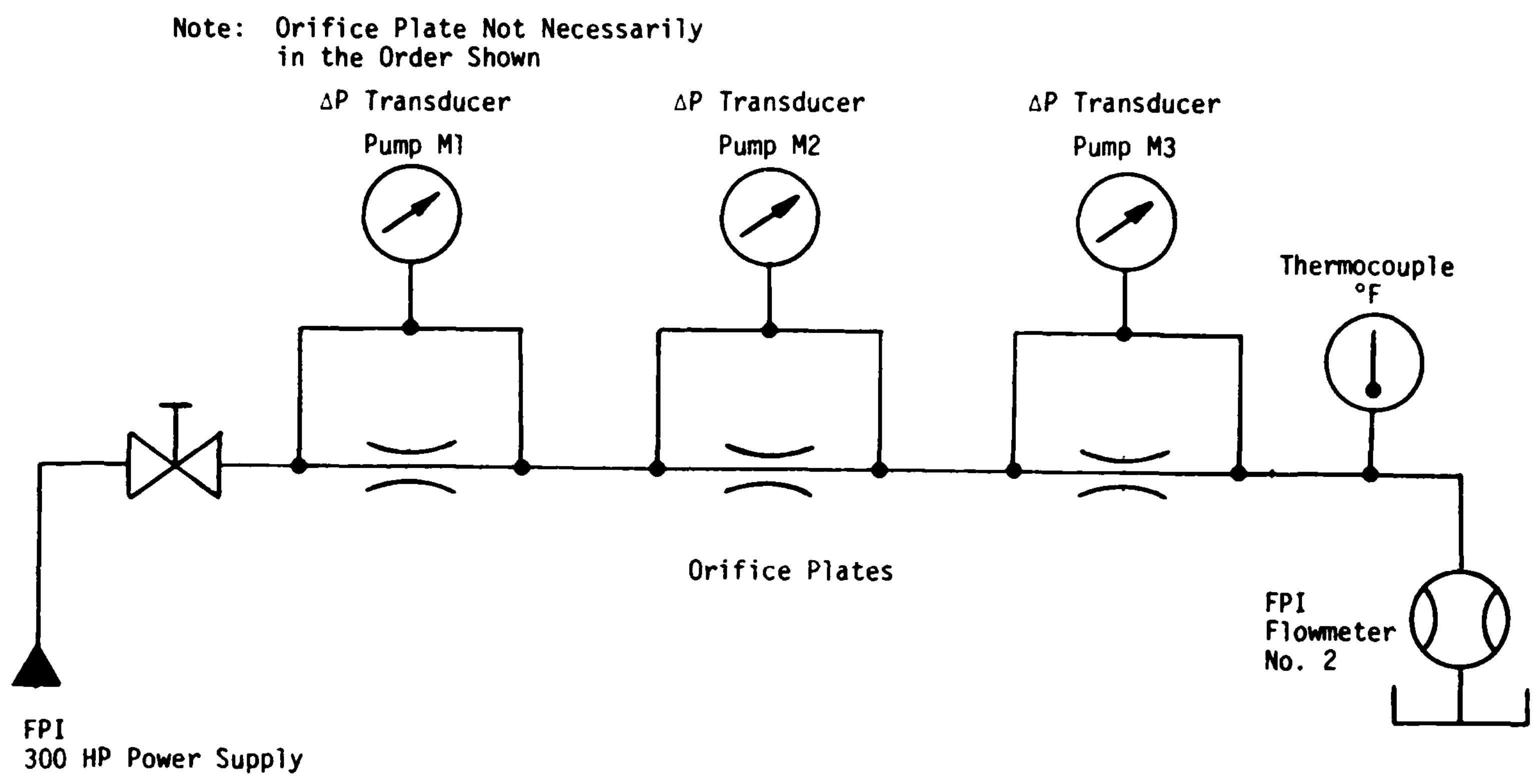


Figure B.2

BLOCK DIAGRAM - ORIFICE PLATE FLOWMETER CALIBRATION SET UP

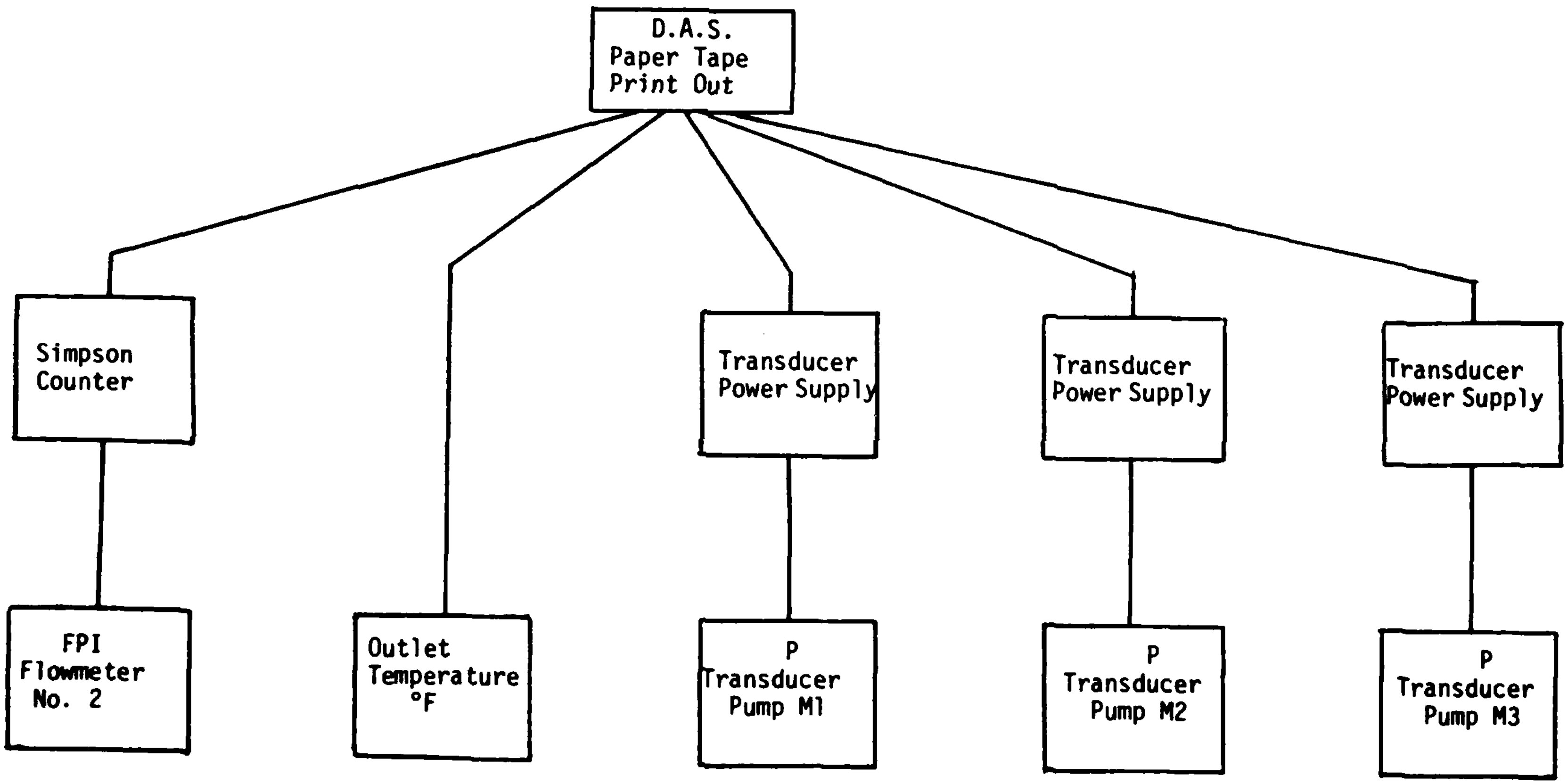


Figure B.3

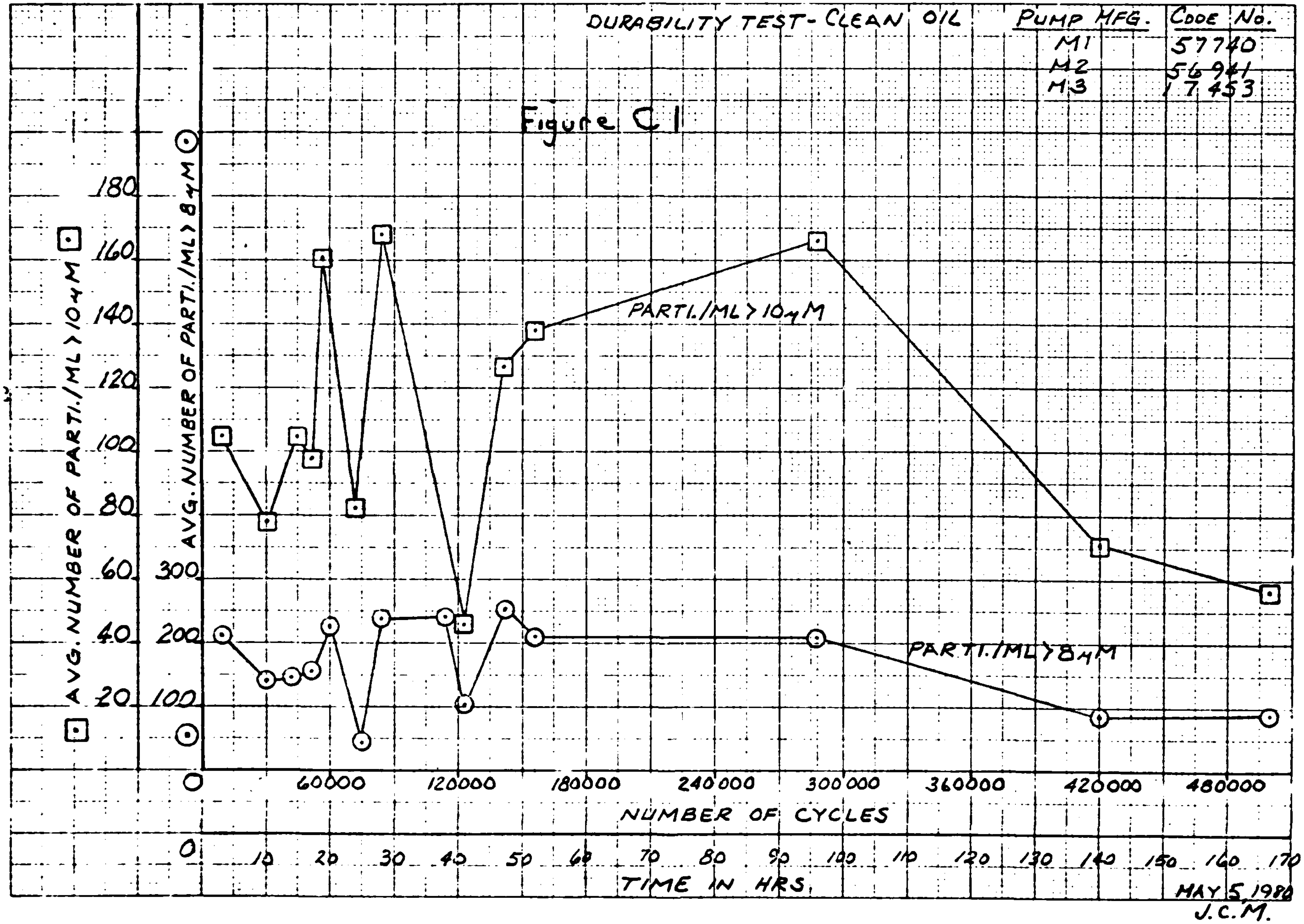
APPENDIX C

GRAPHICAL DURABILITY AND ENDURANCE TEST RESULTS

VERNON McMILLAN, INC., ELIZABETH, N J 07208

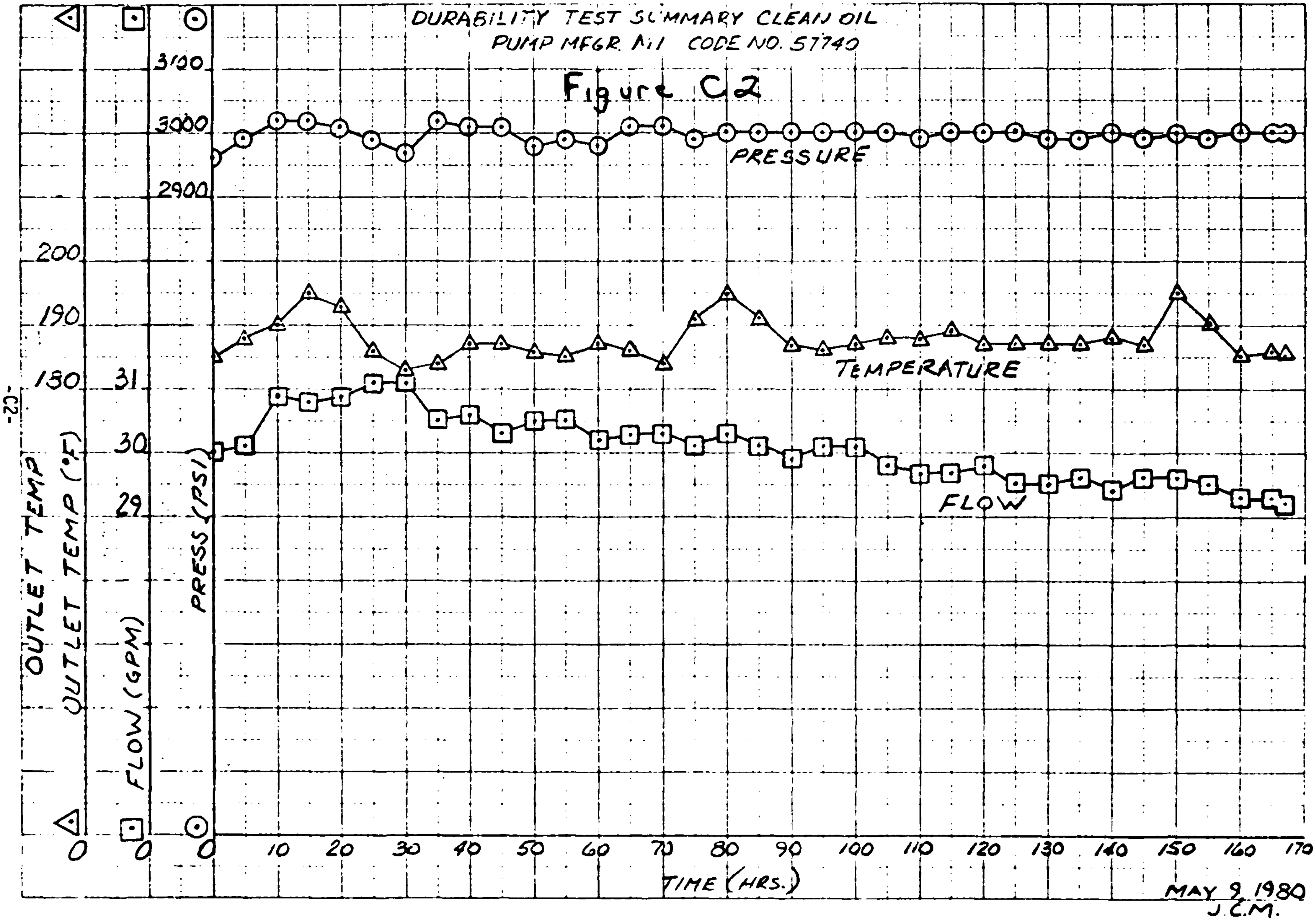
No 19-0920 (R-2470-20) 20 Squares to the inch • Made in U.S.A

Lyon 19-0920 (R-2470-20) 20 Squares to the inch



VERNON McMILLAN, INC. ELIZABETH, N J 07208

No. 19 0920 (R 2470-20) 20 Squares to the inch • Made in U S A



VERNON McMILLAN, INC., ELIZABETH N J 07208
No 19 0920 (R 2470 20) 20 Squares to the inch • Made in U S A
20 Squares to the inch

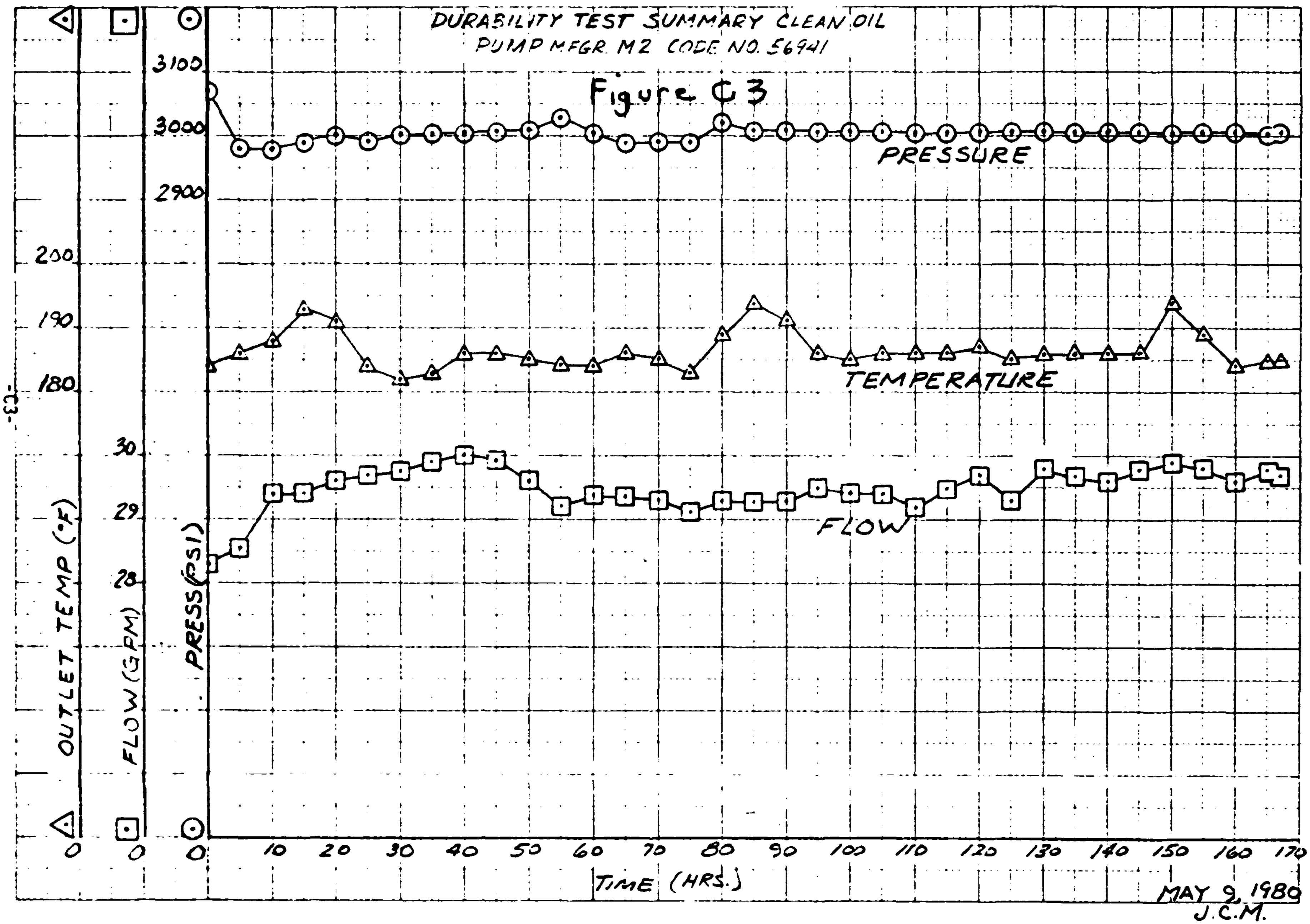
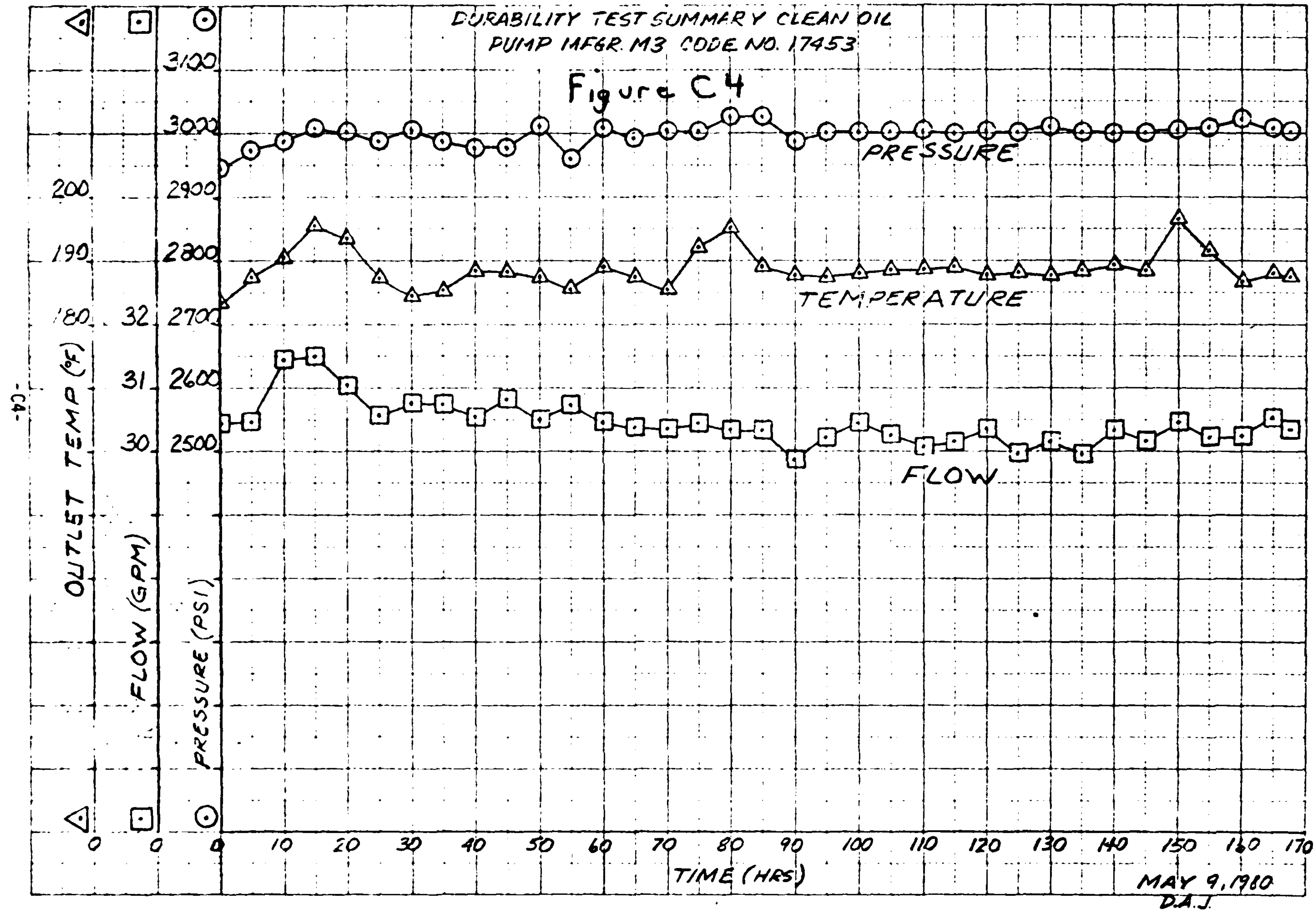


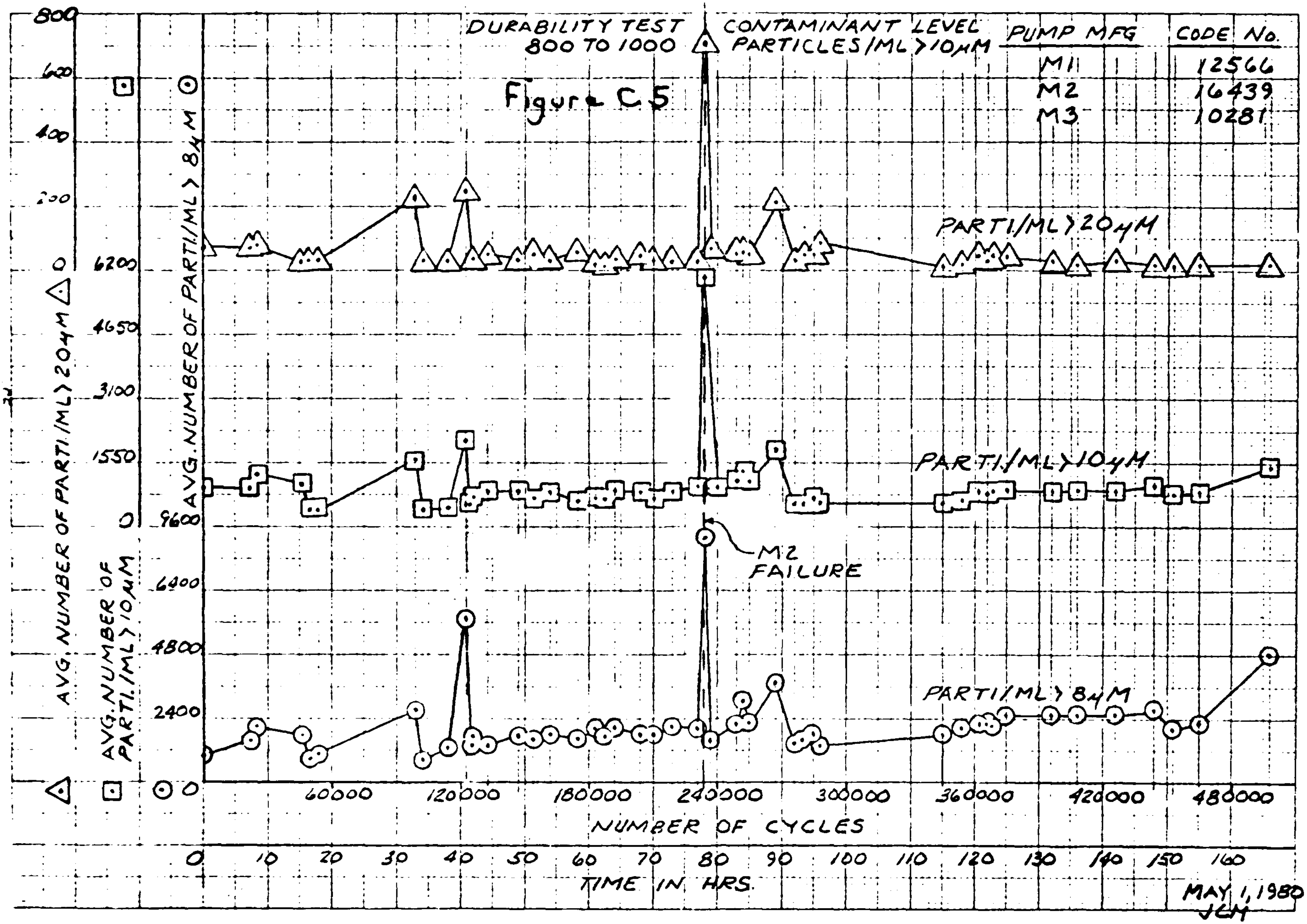
Figure C3

VERNON McMILLAN INC ELIZABETH N J 07208
No 19 0920 (R 2470-20) 20 Squares to the Inch • Made in U.S.A.



VERNON McMILLAN, INC. ELIZABETH, N.J. 07208

No. 19-0920 (R 2470-20) 20 Squares to the inch • Made in U.S.A.



VERNON McMILLAN, INC., ELIZABETH, N J 07208

No. 19 0920 (P-2470-20) 20 Squares to the inch • Made in U S A.

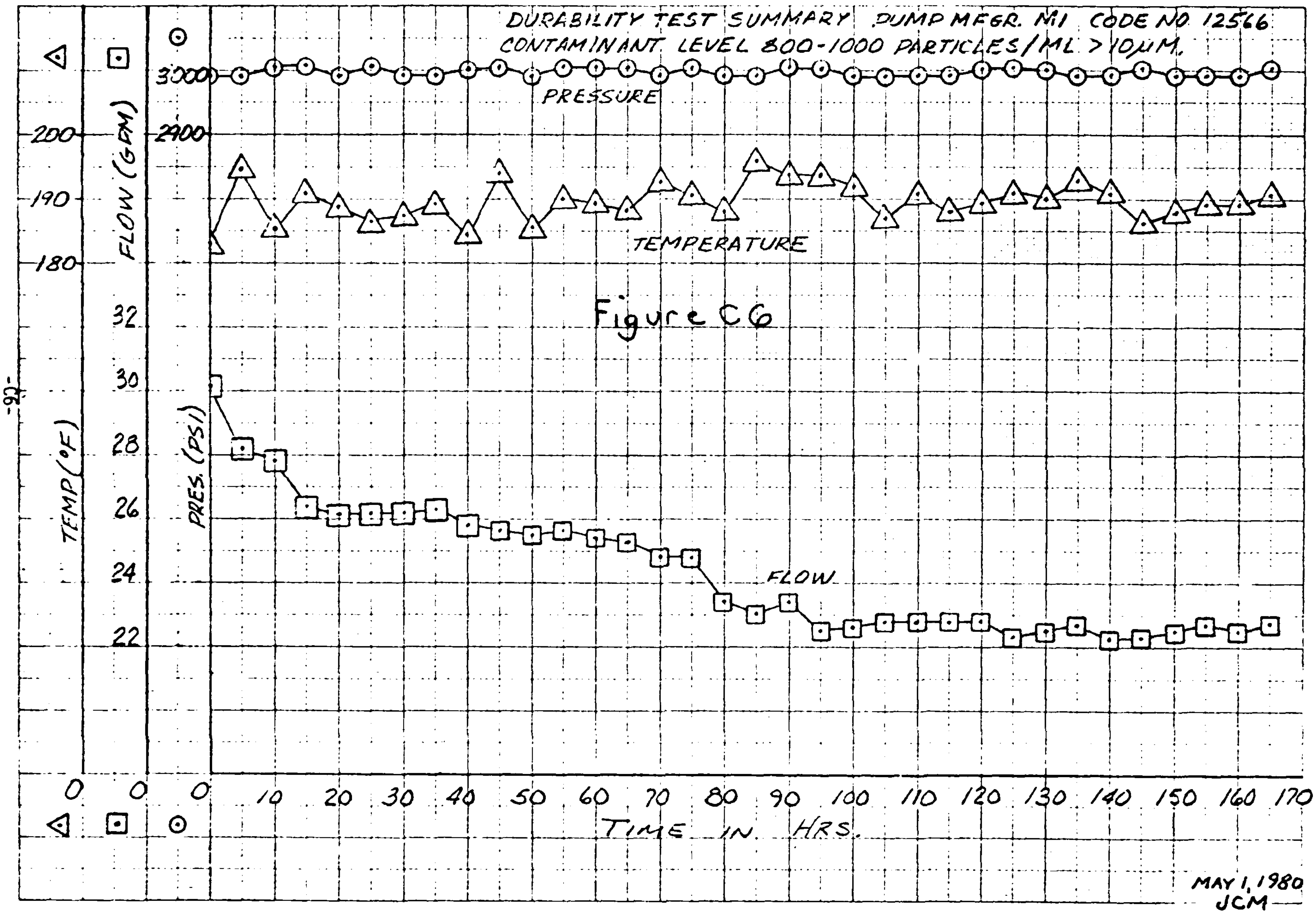


Figure C6

VERNON McMILLAN, INC., ELIZABETH, N.J. 07208

No 19-0920 (R 2470-20) 20 Squares to the inch • Made in U.S.A

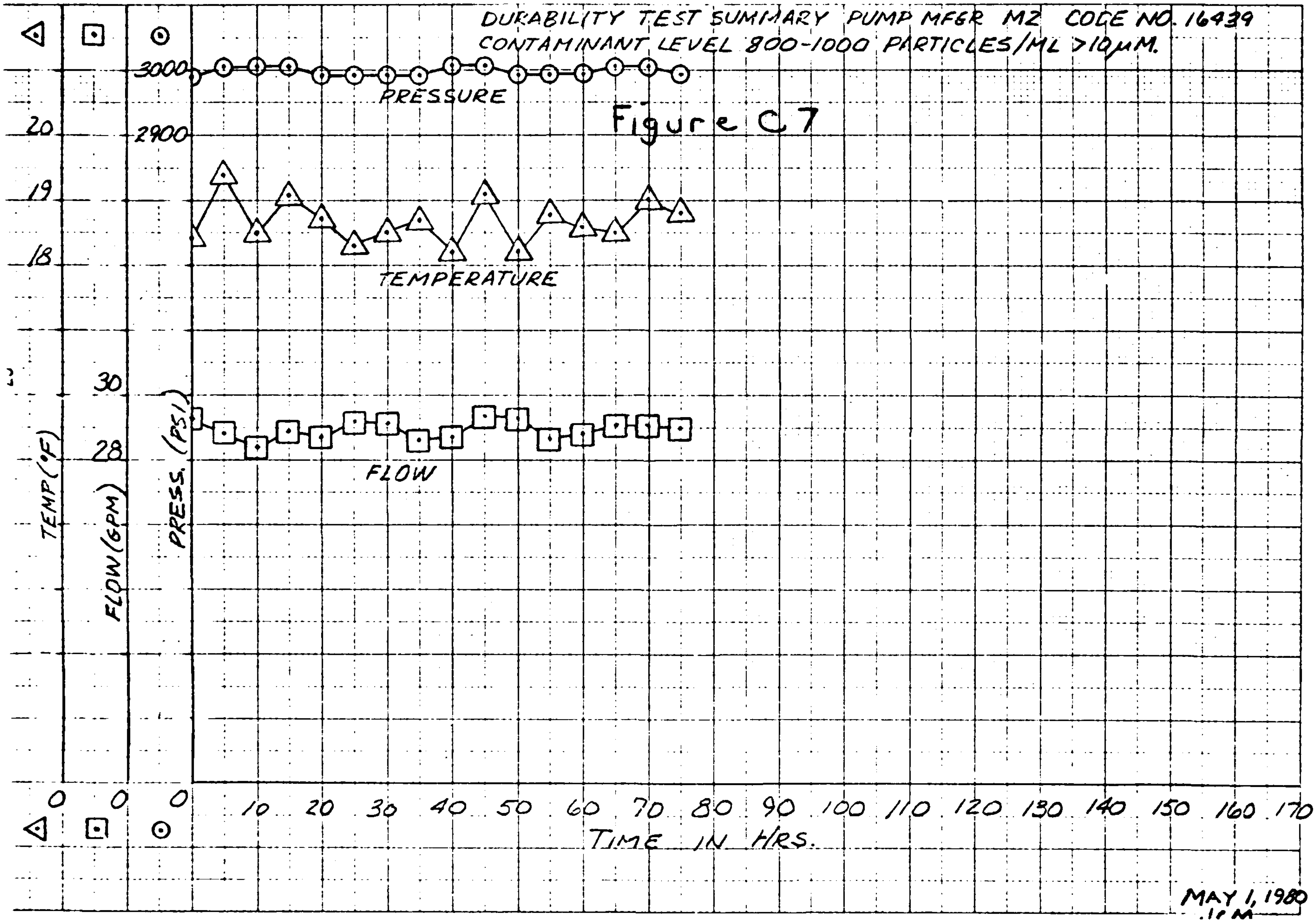


Figure C7

19-0920 (R 2470-20) 20 Squares to the inch

VERNON McMILLAN, INC., ELIZABETH N J 07208

No 19-0920 (R 2470 20) 20 Squares to the inch • Made in U S A

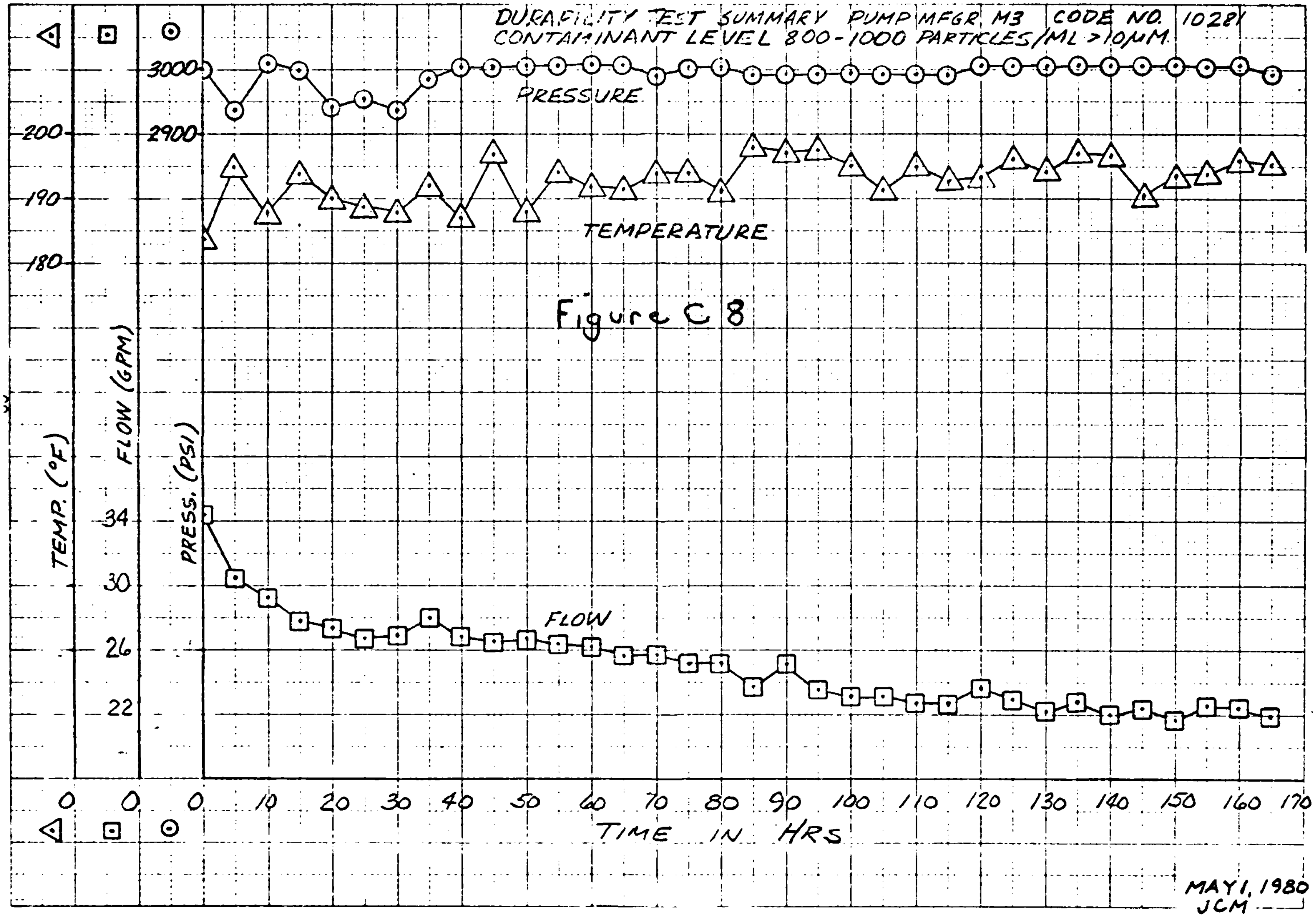


Figure C 8

VERNON McMILLAN, INC., ELIZABETH, N.J. 07208

No. 19-0920 (P 2470-20) 20 Squares to the inch • Made in U.S.A.

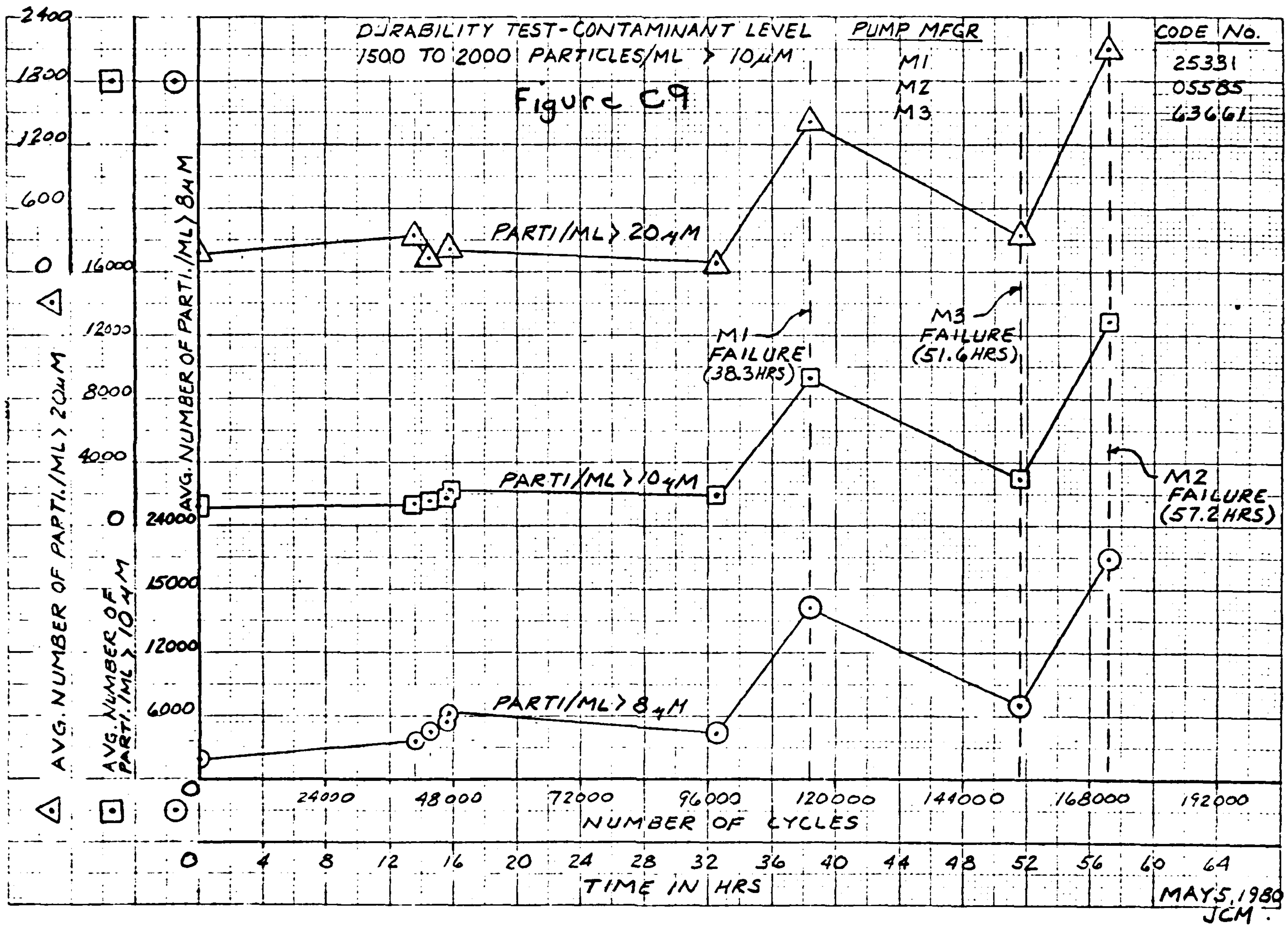


Figure C9

VERNON McMILLAN, INC., ELIZABETH, N.J. 07208 No 19 0920 (R-2470-20) 20 Squares to the inch • Made in U.S.A.

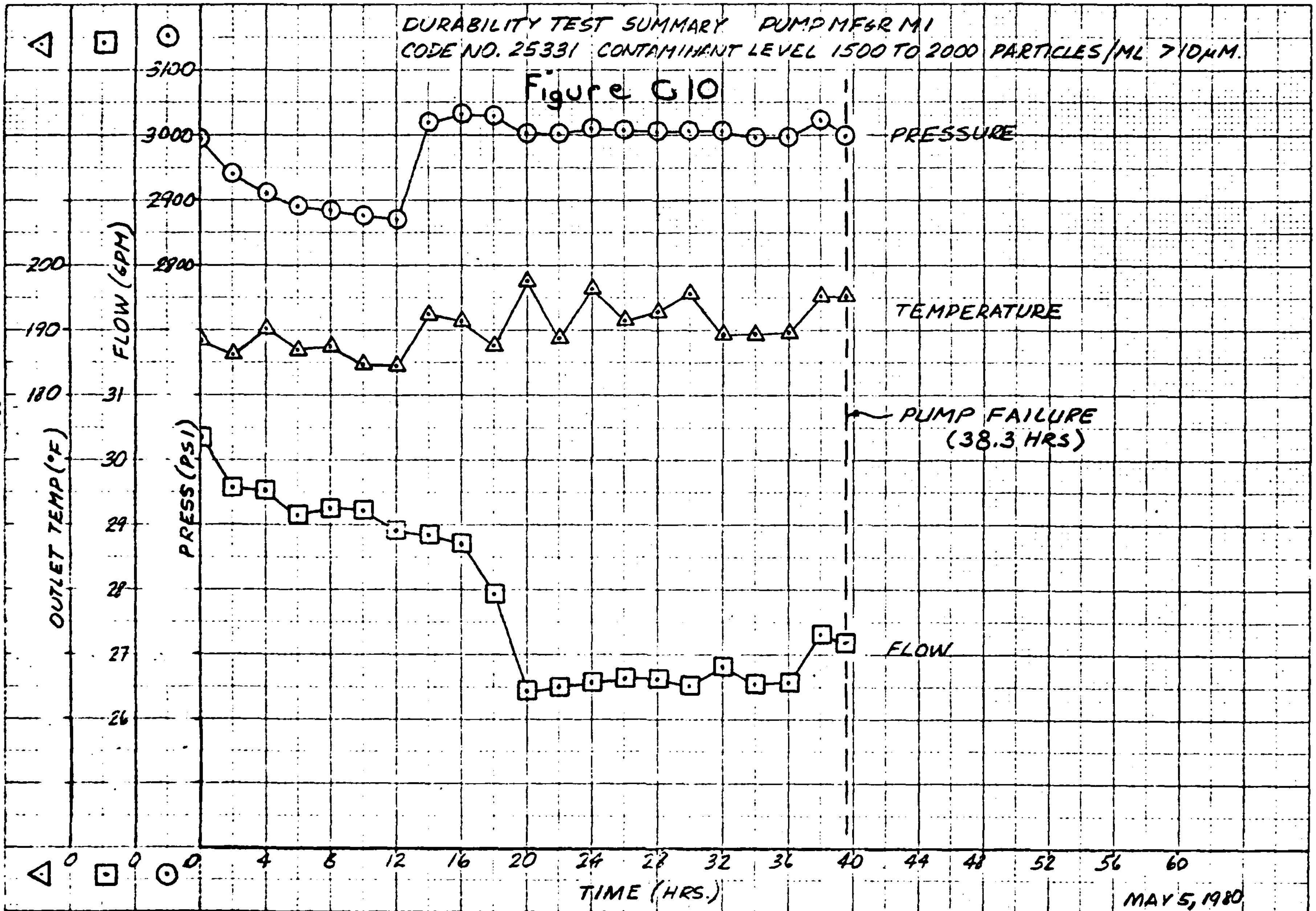


Figure G10

VERNON McMILLAN, INC., ELIZABETH, N J 07208

No 19-0920 (R-2470-20) 20 Squares to the inch • Made in U.S.A.

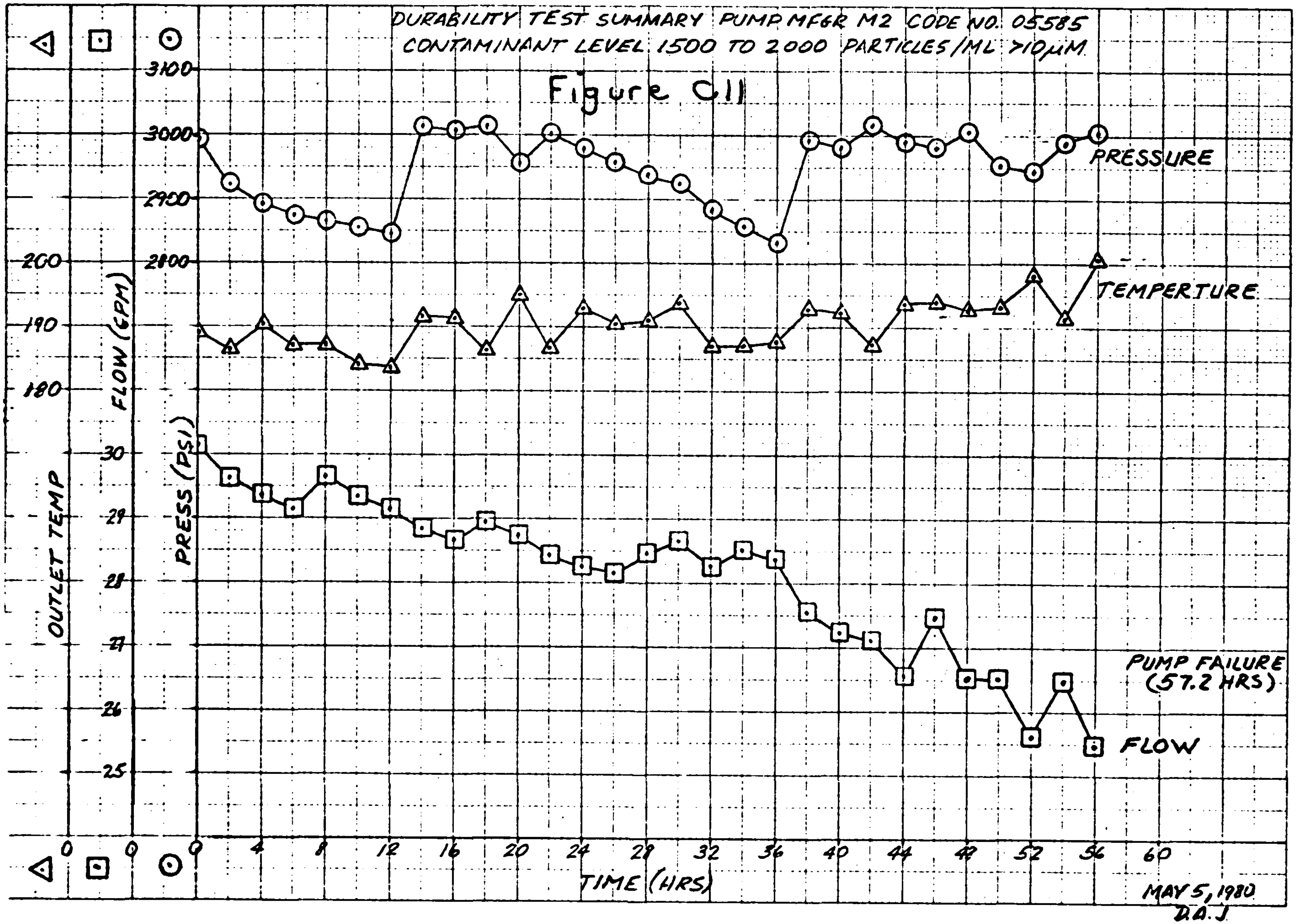
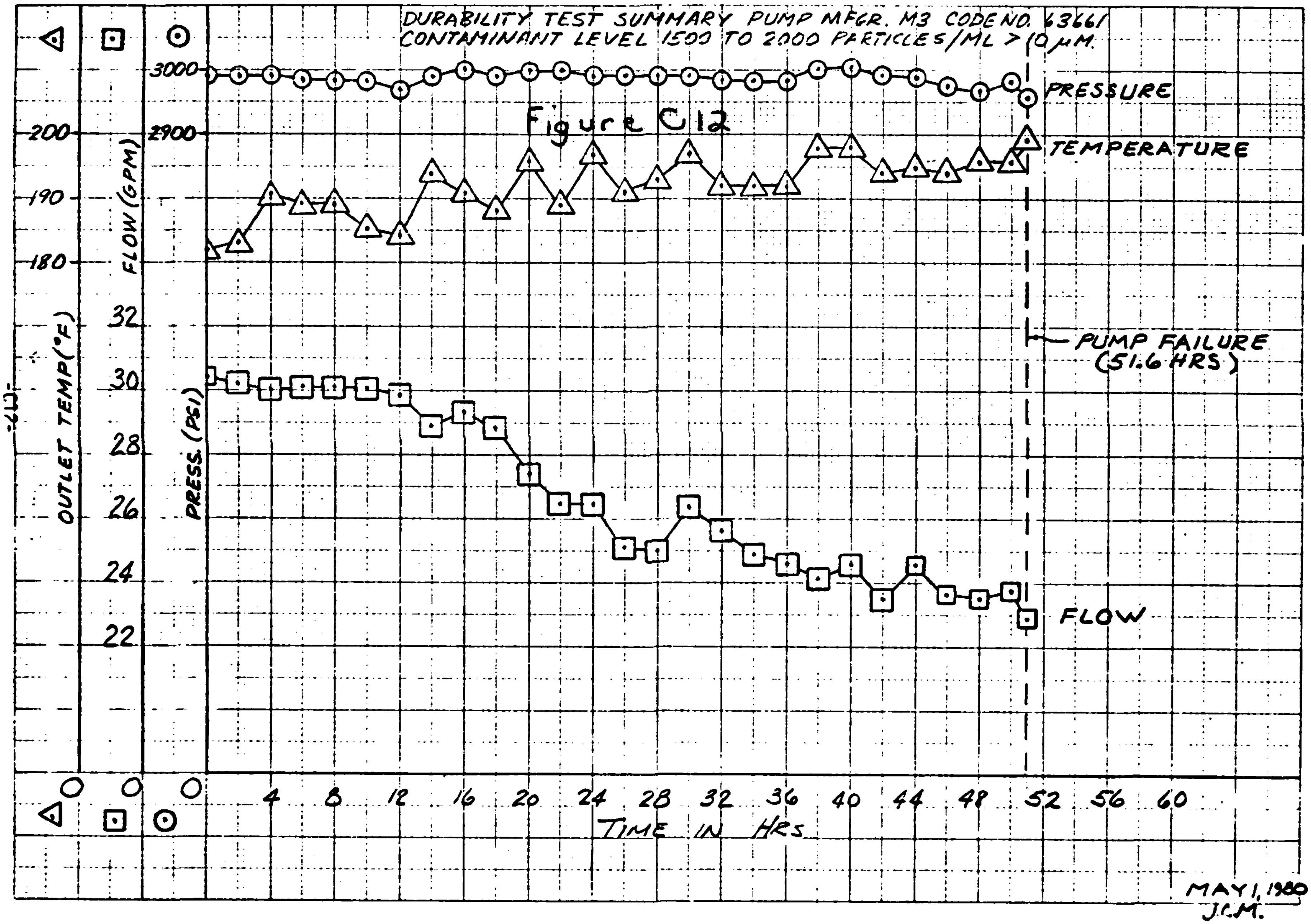


Figure C11

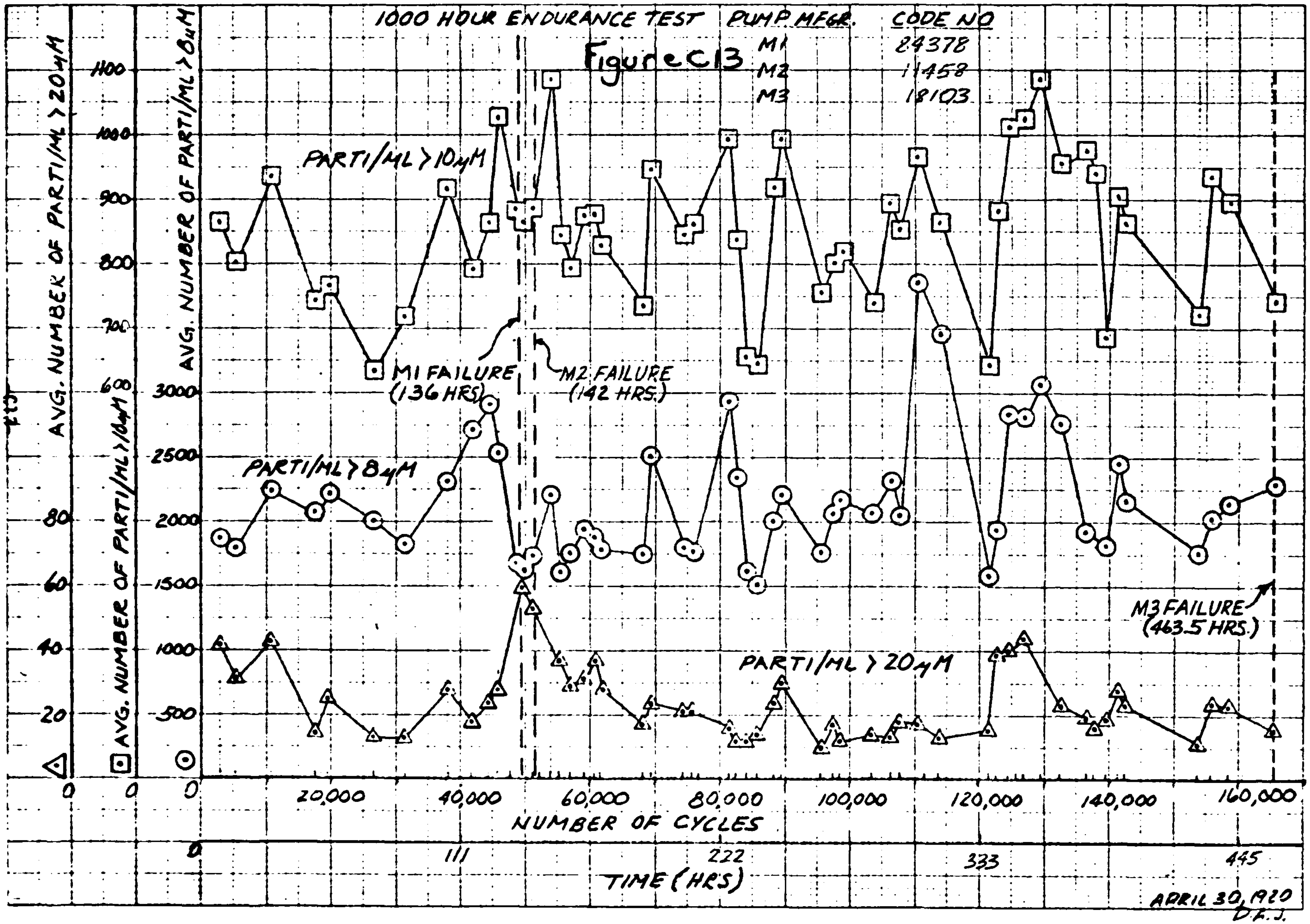
VERNON McMILLAN, INC., ELIZABETH, N J 07208

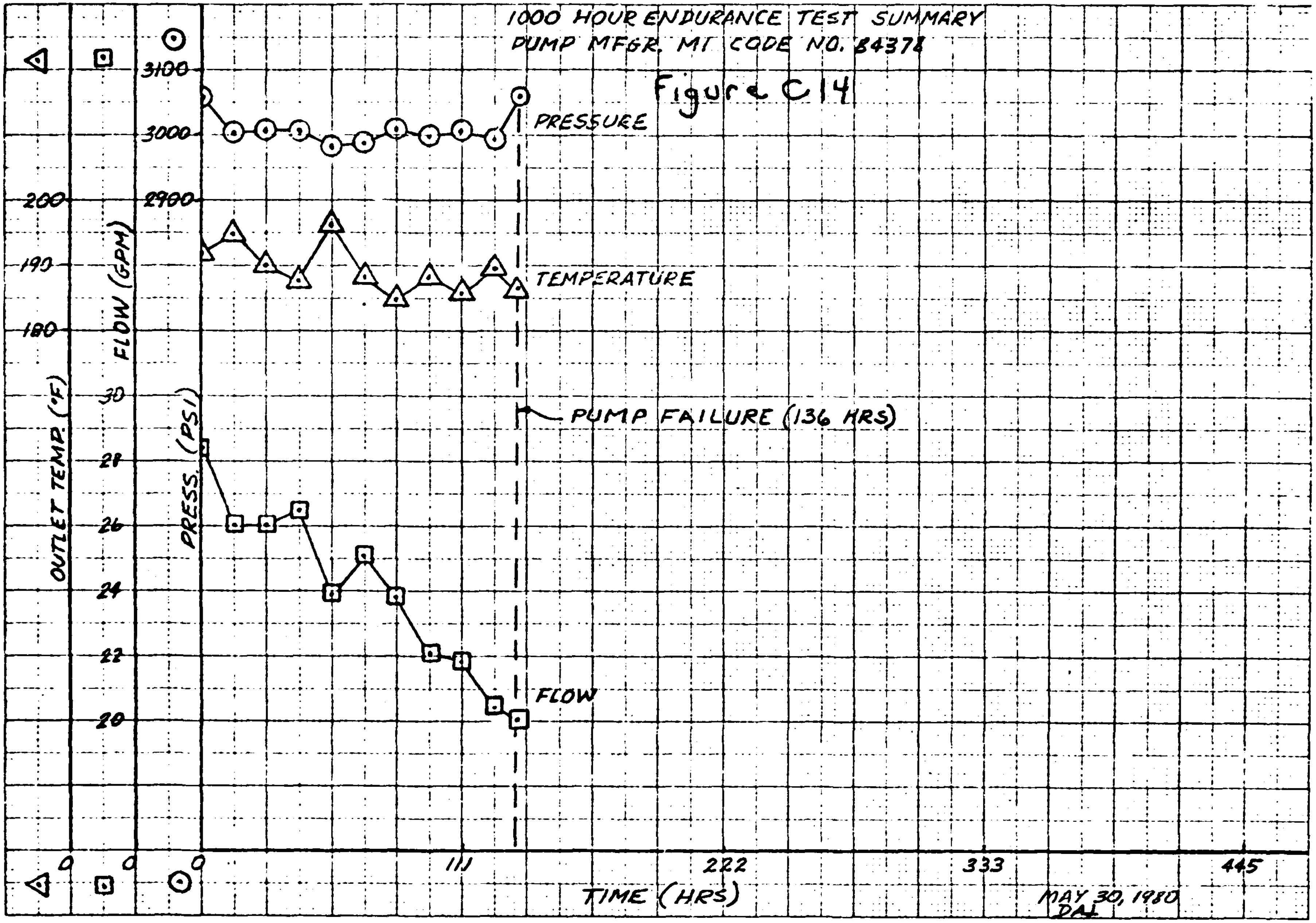
No. 19-0920 (R 2470-20) 20 Squares to the inch • Made in U.S.A.



VERNON McMILLAN, INC., ELIZABETH, N.J. 07208

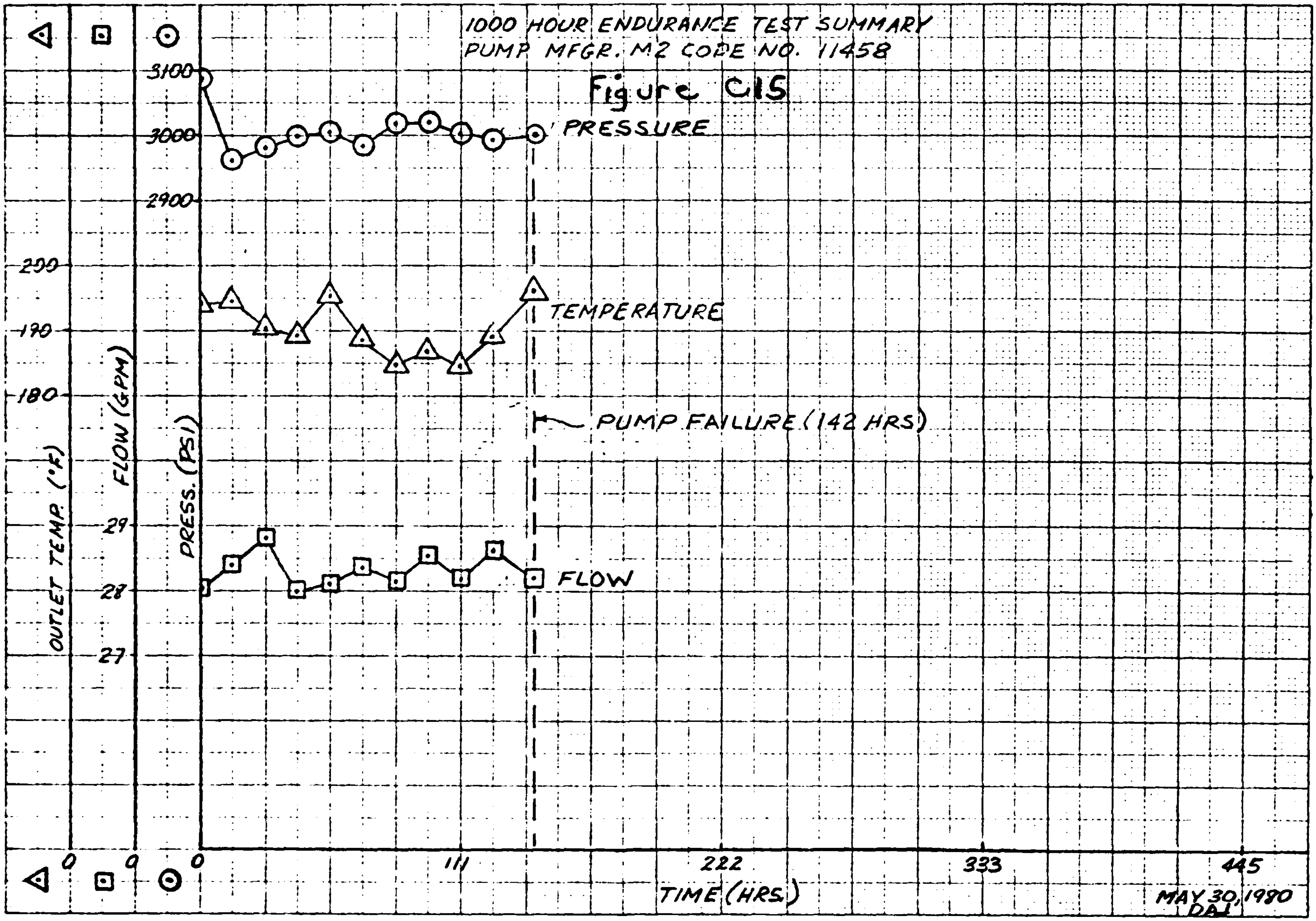
No. 19-0920 (R 2470-20) 20 Squares to the inch • Made in U.S.A.





VERNON McMILLAN, INC. ELIZABETH, N.J. 07208
No. 19-0820 (R 2470-20) 20 Squares to the inch • Made in U.S.A.

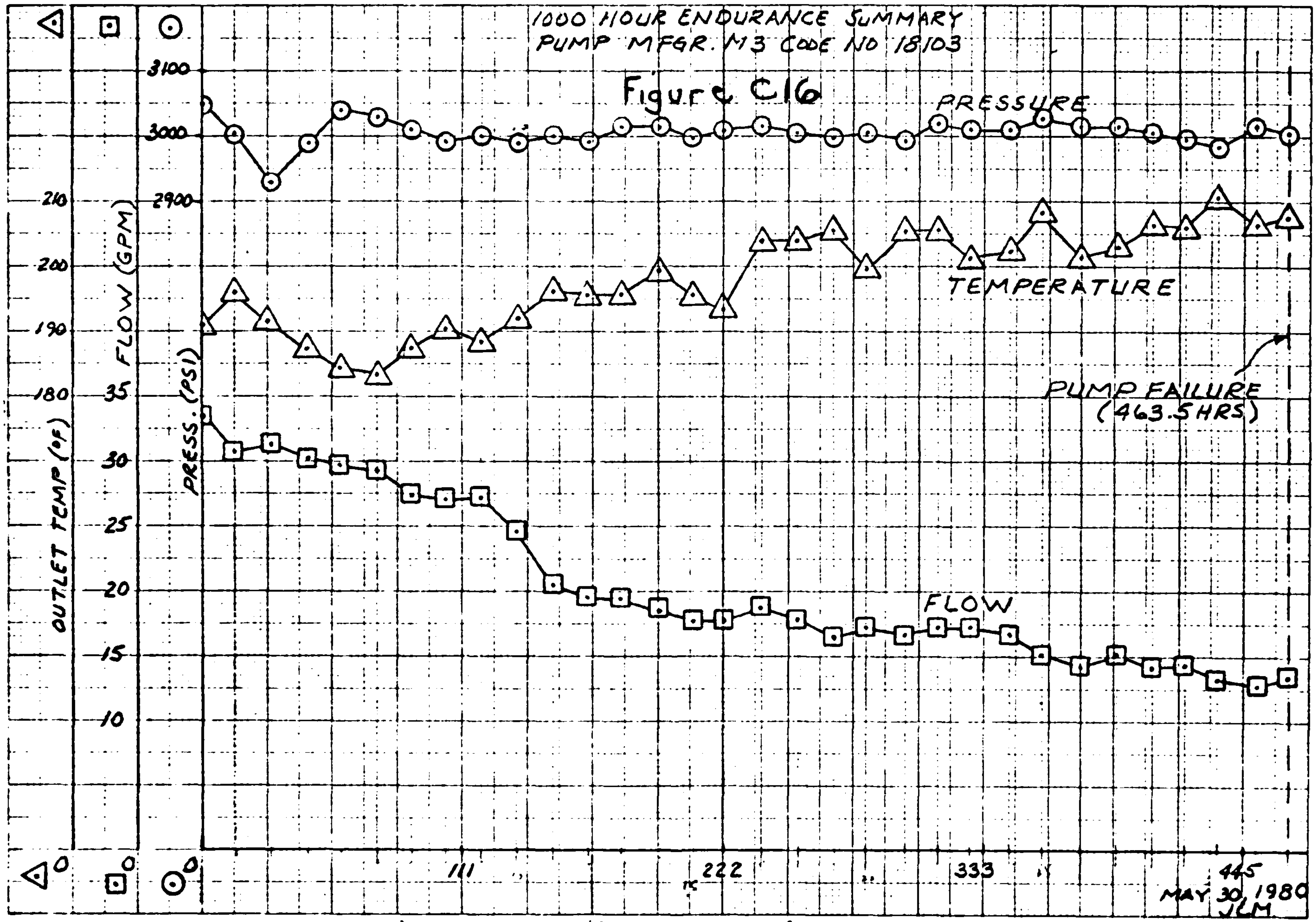
VERNON McMILLAN, INC. ELIZABETH, N.J. 07208 No. 19-0920 (R-2470-20) 20 Squares to the inch • Made in U.S.A.



VERNON McMILLAN, INC., ELIZABETH, N.J. 07208

No 19-0920 (R-2470 20) 20 Squares to the inch • Made in U.S.A.

19-0920 (R 2470-20)
20 Squares to the inch



APPENDIX D

PUMP FAILURE ANALYSIS

PUMP FAILURE ANALYSIS

Durability Test Clean Oil: Less than 200 particles/ml greater than 10 um

Mfgr. No. 1 Pump Code No. 57740

The pump completed the test with a 2.7 percent drop in flow rate and no apparent failure.

Mfgr. No. 2 Pump Code No. 56941

The pump completed the test with a 4.9 percent increase in flow rate and no apparent failure.

Mfgr. No. 3 Pump Code No. 17453

The pump completed the test with a 0.66 percent drop in flow rate and no apparent failure.

Durability Test Dirty Oil: 800-1000 particles/ml greater than 10 um

Mfgr. No. 1 Pump Code No. 12566

The pump completed the test with a 24.5 percent drop in flow rate and no other apparent failures.

Mfgr. No. 2 Pump Code No. 16439 Failure at 227,273 cycles 75 hours

The pump failed to complete the test. Severe wear and scoring of the driven shaft bearings and bearing surfaces caused excessive side play for the driven shaft. The gear teeth tips, wear plates and housing were severly scored and worn from misalignment caused by the excessive side play. Metal pieces were also torn away from the rear wear plate. The wear plates and driven shaft bearings also showed signs of overheating. A crack in the rear cover was found which ran from the driven shaft bearing hole into the drilled hole behind the bearing for lubrication. (Note the driven shaft refers to the shaft which is totally inside the pump and is driven by the other shaft which extends outside the pump and connects to the prime mover. This definition will be used exclusively throughout this report.) (Note the gear tooth tip is the top edge of the tooth that comes in contact with the inside surface of the pump housing. This definition will be used exclusively throughout this report.)

Mfgr. No. 3 Pump Code No. 10281

The pump completed the test with a 35.7 percent drop in flow rate and no other failures.

Durability Test Dirty Oil: 1500-2000 particles/ml greater than 10 um

Mfgr. No. 1 Pump Code No. 25331 Failure at 115,000 cycles 38 hours

The pump failed to complete the test. The driven shaft rear bearing siezed to the shaft and spun inside the housing causing excessive side play on the driven shaft. The excessive side play caused extensive wear and scoring of the wear plates and housing. There were also score marks on the gear teeth from misalignment caused by the excessive side play. Some scoring was also noted on the driven shaft front bearing and both bearing surfaces on the driven shaft were severely scored. The wear plates, driven shaft bearing surfaces and bearings also showed signs of overheating.

Mfgr. No. 2 Pump Code No. 05585 Failure at 171,600 cycles 57 hours

The pump failed to complete the test. Severe wear and scoring of the driven shaft bearings and bearing surfaces caused excessive side play for the driven shaft. The gear teeth tips, wear plates and housing were severly worn and scored from misalignment caused by the excessive side play. The wear plates and driven shaft bearings also showed signs of severe overheating. Pieces of metal were torn away from the rear wear plate.

Mfgr. No. 3 Pump Code No. 63661 Failure at 155,000 cycles 57 hours

The pump failed to complete the test. This pump did not have a catastrophic failure like the previous two. Upon disassembly it was found that there was marginal wear and scoring of the housing, wear plates, and gear teeth tips. There were also signs of overheating on the wear plates. The pump was removed from the test because of excessive noise and unstable outlet pressure. There also was a 25 percent drop in flow rate at the time the pump was removed from the test.

1000 Hr. Endurance Test Dirty Oil: 800-1000 particles/ml greater than 10 um

Mfgr. No. 1 Pump Code No. 84378 Failure at 46,000 cycles 136 hours

The pump failed to complete the test. Severe wear and scoring of driven shaft bearings and bearing surfaces on both ends causing excessive side play. Severe wear and scoring on gear teeth tips, wear plates, and the housing from misalignment caused by excessive side play. The wear plates and driven shaft bearing surfaces showed some signs of overheating.

Mfgr. No. 2 Pump Code No. 11458 Failure at 47,700 cycles 142 hours

The pump failed to complete the test. Severe wear and scoring of driven shaft rear bearing and bearing surface and moderate wear and scoring of driven shaft front bearing and bearing surface caused excessive side play. The housing, front wear plate and gear teeth tips had moderate scoring, while the rear wear plate had severe scoring from misalignment caused by excessive side play. The driven shaft rear bearing and bearing surface and the rear wear plate showed signs of severe overheating, while the housing, gear teeth front wear plate, driven shaft front bearing and bearing surfaces showed slight signs of overheating.

Mfgr. No. 3 Pump Code No. 18102 Failure at 165,500 cycles 464 hours

The test was terminated at a 59.7 percent drop in flow rate per instructions from MERADCOM. The pump was not disassembled for inspection.

APPENDIX E

MERADCOM DURABILITY TEST PROCEDURE

MERADCOM DURABILITY TEST PROCEDURE

28 February, 1978

1.0 SCOPE To provide a method for determining the durability of a fixed displacement, fluid power pump.

2.0 PURPOSE To verify the ability of a pump to perform satisfactorily during a specified period of time when subjected to cyclic discharge pressure at specified conditions of temperature, shaft speed, and system fluid.

3.0 DEFINITION

3.1 Pump Durability The ability of a pump to endure specified operating conditions for an extended period of time.

4.0 PROCEDURE

4.1 Install the pump in the test system as shown in Figure 1 and operate under the following conditions:

4.1.1 Test Oil: All tests will be conducted using oil, lubricating, MIL-L-2104, grade 10 or fluids conforming to SAE J745.

4.1.2 Filtration: The control filter will limit the total number of particles in the system fluid to 1000 particles per milliliter greater than 10 microns.

4.1.3 Instrumentation & Test Parameter Accuracy: Instrumentation must be accurate within the limits set forth in ANSI B93.27.

4.1.4 Inlet Pressure: The pump inlet oil pressure at the inlet fitting will be maintained within 1 in. Hg of atmospheric pressure.

4.1.5 Run-in: Before testing, conduct a two (2) hour pump run-in in accordance with the manufactures recommendations.

4.1.6 Aeration: The inlet oil must be visually free of entrained air throughout testing.

4.1.7 Speed: Manufacturer's Rated Speed.

4.1.8 Pressure Range: From 0 to 115 percent of rated pressure.

4.1.9 Temperature: The inlet oil temperature for the durability test will be maintained at 180°F.

4.1.10 Endurance Cycle Conditions: 60 ± 6 cycles/minute. The waveform is to be consistent with the impulse test waveform of SAE Standard J343. Rate of pressure rise should not exceed 100,000 psi/sec.

4.2 Efficiency: The initial and final pump overall efficiency shall be measured and reported in accordance with SAE J745.

4.3 Test Cycles: The pump shall withstand 500,000 test cycles without leakage or other malfunctions.

4.4 Record any evidence of external leakage or pump malfunction.